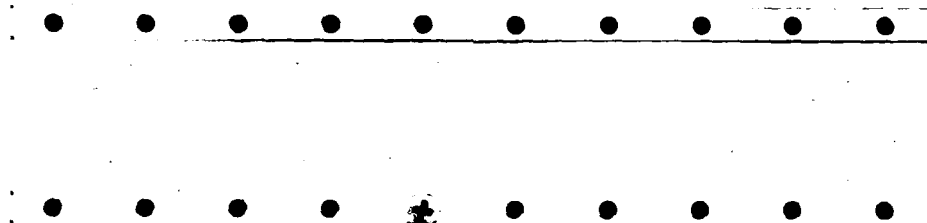




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ANALYZING THE EFFECTS OF TECHNOLOGICAL CHANGE:
A COMPUTABLE GENERAL EQUILIBRIUM APPROACH

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ABSTRACT

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Analyzing the effects of technological changes occurring simultaneously in many sectors of the economy is most meaningfully approached via mathematical models constructed in a general equilibrium framework. In order to be suited to a study of technical change, an equilibrium model should be dynamic, have a long time horizon, and allow production to be disaggregated into a large number of sectors. The size of the resulting model, however, will place it beyond the capability of existing algorithms to solve, unless some special assumptions are made. We describe a class of so-called computable general equilibrium models which have been suitably restricted in order to allow efficient computational implementation. An important example of this class is the PILOT model of the U.S. economy, which combines a process-oriented representation of production with a system of smooth consumer demand functions. Solutions of the PILOT model provide an internally consistent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions in the context of technological change. We report the results of a study using PILOT to assess important differences between a "high-tech" and a "low-tech" economy, in terms of aggregate and sectoral patterns of growth, employment, and energy use over the next 25 years. The scenario analysis presented effectively illustrates the analytical advantages of the general equilibrium perspective. By far the most interesting effects of changing patterns of availability for advanced technology turn out to be indirect effects mediated through shifts in comparative advantage in international trade and through income effects in personal consumption. The only rigorous way to capture such effects is through the use of a general equilibrium analysis.

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EXECUTIVE SUMMARY

In choosing among investment alternatives, research and development strategies, tax policies, energy policies, and in other areas, the long-run consequences of today's actions are frequently the paramount consideration. A dynamic long-term model of the economy can be a valuable tool in making these decisions, giving decision-makers a means to generate internally consistent hypothetical scenarios of future events, to evaluate the effects of their actions under those hypotheses, and to choose among alternatives on the basis of measurable criteria. The appropriate theoretical framework for investigating phenomena with economy-wide consequences is that of a general equilibrium, that is, a set of prices and corresponding quantities which balance the supply and demand for all commodities in the economy.

The principal focus of the present study is on the long-run economic effects of technological change. While general equilibrium is a natural vehicle for conducting such a study, this approach has not been extensively used in the past. The primary obstacle has been computational complexity — analyzing the effects of technological change requires a dynamic model with a great deal of sectoral detail, resulting in a very large model. In the body of the report, we seek first to demonstrate why a general equilibrium framework is appropriate for analyzing the economic effects of technological change. From this starting point we enumerate a set of characteristics needed in a general equilibrium model in order to represent the most interesting features of technical change. We then discuss some simplifying assumptions which can be used to produce a model that is amenable to solution on a computer. As a working illustration of these ideas, we present the PILOT model of the U.S. economy and the results of an analytical study based on four model scenarios depicting alternative patterns and rates of technological innovation.

Why general equilibrium?

A change in technology, even if localized in its direct effects, is likely to have indirect effects throughout the economy which are more important than the direct ones, even to the sector experiencing the technical change. In particular, any technical change which improves the productivity of a production process will increase income, and thus affect the demand for all commodities. The sector which experienced the technical change will see demand for its output increase, either for sales to consumers or for sales as an intermediate input in other production processes. A model of the entire economy is needed to follow through all of these indirect effects, since no analysis which looks at a particular sector and treats the rest of the economy "*ceteris paribus*" will produce the correct results for an economy in which

these linkages and income effects are important. It is also essential to be able to represent technological changes which simultaneously affect many sectors or production processes. Automation is such a change. Factory and office automation will affect every sector in the economy. In the face of such a pervasive new technology, the indirect linkages throughout the economy are even more important. It is impossible to simply "add up" the direct effects on various sectors and thereby obtain a reasonable analysis of the economy-wide effects of such a technical change. A comprehensive model of the economy is the only tool which will enable us to meaningfully examine these economy-wide effects.

The general equilibrium framework is widely accepted as the most plausible way to model the evolution of the economy in the absence of detailed information on the decision rules followed by individual agents. Such information is, of course, not available beyond the very immediate future. We accordingly believe that general equilibrium is a powerful and defensible modeling paradigm for analyzing long-run economic trends, particularly when addressing significant structural changes in the economy such as those that accompany major technological innovation. Since significant structural change, by definition, takes us outside the range of historical production relationships, any modeling technique which relies primarily on a statistical analysis of history is necessarily unsuited to addressing the potential effects of such change. In contrast, we develop in this research a rigorous general equilibrium model that has a natural structure which can be meaningfully modified to represent expected future technology. Supporting this construction is a substantial body of experience that has been accumulated in formulating economic equilibrium problems and in computing solutions to them.

Features needed in the model

In this research we are primarily interested in questions about the performance of the economy as a whole and not in the specific actions of individual consumers or firms. In particular, this means that we can consider models in which total national income is determined, but not the distribution of income among individuals. We are also primarily interested in process innovations and those product innovations which result in a new product that can be readily substituted for another in a production process or in consumption. Technological changes of this sort directly affect only producers, not consumers. As a consequence of these two considerations, we can focus attention on models which represent the decisions of producers in detail and treat consumers in a less detailed way. This feature distinguishes technology-oriented models from models in which the behavior of individual consumers is important, as is the case in most models used for tax policy analysis, for example.

Analyzing technical change places two main requirements on a model, the first having to do with time and the second with aggregation. Technical change occurs over time, and agents in the economy have to make decisions in early periods (such as investing in

facilities which embody a particular technique) which will have effects over many subsequent periods. In this context, it is essential to have a fully dynamic model that determines an equilibrium time path of prices and actions into the future. The second requirement arises from a desire to disaggregate industry sectors to a level at which processes and products are sufficiently homogeneous to allow for a meaningful engineering analysis of the opportunities for technological innovation. As a result, dozens of commodities and sectors are necessary.

The PILOT model

Consideration of the above requirements has significantly influenced the structure of PILOT, a large-scale dynamic general equilibrium model of the U.S. economy. In order to take full advantage of engineering analysis as a basis for defining new or hypothetical technological alternatives, the production sector is modeled using the proven techniques of activity analysis (or linear process modeling). The general equilibrium framework integrates this representation of production with a system of smooth consumer demand functions. Solutions of the model provide a coherent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions in the context of technological change. In particular, the model can be used to assess the effects of different time paths of availability and/or technical characteristics of new technologies.

PILOT's activity analysis representation of production goes beyond traditional fixed-coefficient input/output analysis by defining multiple columns for each sector representing alternative production technologies for new investments. The energy-producing sectors of the economy as well as energy-use decisions in manufacturing and in residential and commercial buildings are represented via modular process models. The productive capital stock is vintaged and unmalleable once in place. Domestic industries compete with imports (whose prices are given exogenously) and face a downward-sloping export demand schedule (also exogenous). The exchange rate is determined endogenously. Final demand is represented via a government input/output sector, endogenous investment activity in all sectors, and consumer demand for 13 aggregate commodities. *Per capita* demand for 5 of these consumption aggregates is specified exogenously. Demand for the other 8 is a function of prices and income, modeled via an aggregate quadratic utility function.

PILOT directly represents economic activities and relations in each of nine periods of five years in length, covering the time horizon 1975-2015. A given activity representing a long-lived investment may have coefficients in the relations of many subsequent periods. It may also have coefficients in the relations of one or more previous periods to the extent that the investment requires a substantial construction lead time. Since decisions to undertake these long-lived investments are made with perfect foresight, an equilibrium solution must be calculated simultaneously across all time periods.

A study of technological change

The present study employs the unique capabilities of PILOT to assess important differences between a "high-tech" and a "low-tech" economy, in terms of aggregate and sectoral patterns of growth, employment, and energy use over the next 25 years. While we may reasonably expect the direct effects of high technology to be labor-saving and somewhat energy-saving (though perhaps more electricity intensive), the indirect effects of higher economic growth, different import-export patterns, and different rates of growth in the various economic sectors are likely to be more important in determining overall patterns. An integrated, technology-oriented model such as PILOT can be profitably employed to evaluate the net effects of the whole array of economic forces at work. A broadly focused study of alternative energy/economic futures can provide a valuable perspective on general trends and magnitudes which would not be available from a more issue-specific analysis.

To this end we have developed a slate of four model scenarios designed to isolate a pure effect of delays in the availability of new technology. One scenario is designated as a base case, and each of three delay scenarios progressively subjects more industry groups or technologies to a delay. The first focuses on information processing technologies in the service industries and government. The second extends the delays to the manufacturing sectors, with a primary emphasis on electronics-related automation. The final delay scenario indirectly delays technologies which have no explicit representation in the model by reducing assumed rates of productivity growth in the industries using these technologies. For purposes of the scenario comparison, the cause of the delays in technology availability is not important. Any number of technical or economic factors, external to PILOT, could delay the introduction dates hypothesized in the base case. The usefulness of PILOT is not in modeling how and why technical advances are made but in assessing the potential utilization of new technologies and the associated effects on the economy as a whole.

The technology specifications and availability patterns characterizing the base case and delayed technology scenarios give rise to four distinct general equilibrium solutions of the PILOT model. By comparing economic measures across these solutions, we may begin to draw some meaningful conclusions about the basic economic effects of the kinds of technological change that is modeled. In the report, we present the salient results of this scenario analysis and attempt to analyze the underlying economic and technological forces which account for the observed differences in economic performance across the four scenarios.

The most important result which emerges from this analysis is that delaying the availability of new technologies significantly reduces overall economic performance, which is not unexpected. Over the 1985-2010 horizon, GNP grows at an average annual rate of 2.9 percent in the base case. This growth rate drops monotonically through the delay cases to a low of 2.2 percent. Over 25 years the average annual rate of growth in consumption falls from 2.7 percent to 2.0 percent between the base case and the worst case. These differences in growth

rates of GNP and consumption compound to a divergence across scenarios of 13-16 percent by 2010. Investment expenditures show more variation across scenarios than do consumption and GNP as a whole. The average annual rate of growth in investment declines from 2.8 percent in the base case to 2.0-2.2 percent in the delay cases. The compounded effect by 2010 is a 27 percent drop between base case and the worst case.

Our analysis also results in some conclusions that are unexpected, particularly when it is focussed at the level of individual sectors. Some sectors are found to be quite sensitive to changes in total income. Construction is one such sector. The indirect effects on the construction industry of delaying availability of new technologies in other sectors, mediated by changes in income, are large — even though the direct effects are small. Some sectors are strongly affected by changes in patterns of imports and exports which result from technology delays in other sectors. The chemicals and primary metals industries, for example, have higher output in some of the delay cases than they do in the base case, because imports of them are reduced so that other commodities can be imported instead. Some of the effects on energy consumption of the technology delays we have studied are also quite unexpected. Energy consumption is found to be much more sensitive to changes in the output of certain industries than it is to changes in overall economic performance, and the industries which affect energy consumption most are some of those for which output is least highly correlated with GNP.

We have found that the economic costs of delaying new technology can be large, implying that public policies should be carefully examined to assess their interaction with the development and domestic utilization of new production technology. Government funding of research and development, R & D tax credits, investment tax credits, and patent and copyright laws are all public policies which have important and direct effects on the adoption of advanced technologies. In addition, foreign trade policy may have significant indirect effects. Our results show that dramatic changes in import/export patterns are an important mechanism for mediating the effects of changes in technological innovation, which points to the existence of important relationships between technological change and patterns of trade that are not limited to the one-way causal link addressed in this study.

We believe that the methodological development and scenario analysis presented in this paper effectively demonstrate the feasibility and desirability of a computable general equilibrium approach to analyzing the economy-wide effects of a phenomenon such as technological change. By far the most interesting effects of changing patterns of availability for advanced technology turn out to be *indirect* effects mediated through shifts in comparative advantage in international trade and through income effects in personal consumption. The only rigorous way to capture such effects is through the use of a general equilibrium analysis.

INTRODUCTION

In choosing among investment alternatives, research and development strategies, tax policies, energy policies, and in other areas, the long-run consequences of today's actions are frequently the paramount consideration. A dynamic long-term model of the economy can be a valuable tool in making these decisions, giving decision-makers a means to generate internally consistent hypothetical scenarios of future events, to evaluate the effects of their actions under those hypotheses, and to choose among alternatives on the basis of measurable criteria. In order to be useful in such a context, a model must satisfy a stringent set of conditions. It must be a comprehensive representation of the major forces which will affect the development of the economy over the relevant time horizon, including technological innovation, changing consumer tastes, competition from other countries, and rising energy and natural resource prices. It must be able to represent a wide variety of possible futures, as determined by variations in technological opportunities, government policies, and world market conditions. Model structure and scenarios must be consistent with reasonable beliefs about the behavior of economic agents. Finally, the model must admit to solution using current computation technology.

We believe that the appropriate theoretical framework for investigating phenomena with economy-wide consequences is that of a general equilibrium, that is, a set of prices and corresponding quantities which balance the supply and demand for all commodities in the economy. The term general equilibrium applies to both the market-clearing prices and quantities, themselves, and to the "invisible hand" mechanism by which competitive markets are cleared. The concept of equilibrium is an old one, but it is also one for which current interest is both diverse and intense. The advent of the computer has given rise to a class of so-called *computable* general equilibrium (CGE) models, which may be distinguished by the explicit intent to numerically represent the equilibrium system, compute a solution of the system, and derive policy or other conclusions by comparing solutions across different model specifications.

The principal focus of the present study is on the long-run economic effects of technological change. While computable general equilibrium is a natural vehicle for conducting such a study, this approach has not been extensively used in the past. The primary obstacle has been computational complexity — analyzing the effects of technological change requires a dynamic model with a great deal of sectoral detail, resulting in a very large model. In this report, we seek first to demonstrate why a general equilibrium framework is appropriate for analyzing the economic effects of technological change. From this starting point we enumerate a set of characteristics needed in a general equilibrium model in order to represent

the most interesting features of technical change. We then discuss a body of simplifying assumptions which can be used to produce a model that is amenable to solution on a computer. As a working illustration of these ideas, we present the PILOT model of the U.S. economy and the results of an analytical study based on four model scenarios depicting alternative patterns and rates of technological innovation.

1.1 Why general equilibrium?

A change in technology, even if localized in its direct effects, is likely to have indirect effects throughout the economy which are more important than the direct ones, even to the sector experiencing the technical change. In particular, any technical change which improves the productivity of a production process will increase income, and thus affect the demand for all commodities. The sector which experienced the technical change will see demand for its output increase, either for sales to consumers or for sales as an intermediate input in other production processes. A model of the entire economy is needed to follow through all of these indirect effects, since no analysis which looks at a particular sector and treats the rest of the economy "*ceteris paribus*" will produce the correct results for an economy in which these linkages and income effects are important. It is also essential to be able to represent technological changes which simultaneously affect many sectors or production processes. Automation is such a change. Factory and office automation will affect every sector in the economy. In the face of such a pervasive new technology, the indirect linkages throughout the economy are even more important. It is impossible to simply "add up" the direct effects on various sectors and thereby obtain a reasonable analysis of the economy-wide effects of such a technical change. A comprehensive model of the economy is the only tool which will enable us to meaningfully examine these economy-wide effects.

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1.2 Features needed in the model

In order to define the features needed in a model for analyzing technical change, it is necessary first to identify the class of questions to be addressed. In this research we are primarily interested in questions about the performance of the economy as a whole and not in the specific actions of individual consumers or firms. In particular, this means that we can consider models in which total national income is determined, but not the distribution of income among individuals. We are also primarily interested in process innovations and those product innovations which result in a new product that can be readily substituted for another in a production process or in consumption. Technological changes of this sort directly affect only producers, not consumers. As a consequence of these two considerations, we can focus attention on models which represent the decisions of producers in detail and treat consumers in a less detailed way. This feature distinguishes technology-oriented models from models in which the behavior of individual consumers is important, as is the case in most models used for tax policy analysis, for example.

Analyzing technical change places two main requirements on a model, the first having to do with time and the second with aggregation. Technical change occurs over time, and agents in the economy have to make decisions in early periods (such as investing in facilities which embody a particular technique) which will have effects over many subsequent periods. Since the expectations of agents about the future are important in determining agents' actions, it is important to represent these expectations in the model. In general equilibrium analysis it is customary to assume that agents know what the economic structure will be in the future and correctly anticipate future equilibrium prices, contingent on the realization of any sources of uncertainty. (If there is no uncertainty, this feature is typically referred to as perfect foresight or perfect look-ahead.) In this context, it is essential to have a fully dynamic model that determines an equilibrium time path of prices and actions into the future. The time horizon of the model should be at least as long as the effects of near-term decisions persist. Since we are interested in decisions about investments in plant and machinery with lifetimes of at least ten to fifteen years, the model horizon must stretch from today past the year 2000, and preferably to 2010 or 2020.

The second requirement which the objective of analyzing technical change places on a model has to do with the level of aggregation of commodities and industry sectors. Consider the automobile and precision machinery sectors, for example. Assembling an automobile and assembling a piece of precision machinery may be conceptually similar ("insert the bolt through the hole and tighten the nut"), but there are important differences between an assembly line producing thousands of identical units per day and a batch assembly process producing only a few units. The automation technologies required are quite different, and likely to have very different effects. Our desire is to disaggregate industry sectors to a level at which processes and products are sufficiently homogeneous to allow for a meaningful engineering analysis of the opportunities for automation. As a result, dozens of commodities

and sectors are necessary, and it would be desirable to have hundreds, working at the level of aggregation of the large input/output tables.

This degree of disaggregation, added to the requirement of a fully dynamic structure, results in models with many thousands of prices and activities. Solving a model of such a size would be impractical with the computational techniques available today for arbitrary general equilibrium problems. As a consequence, we are obliged to make certain simplifying assumptions with respect to the representation of decision-making by consumers and producers. These assumptions and the corresponding model structures are developed and justified in Section 2. In working with the PILOT model, we further simplify the general equilibrium framework by assuming that there is no uncertainty and that markets are complete. This simplification permits the use of a physical flow model which requires no explicit representation of financial instruments, including money. The end result is a model for which a general equilibrium solution can be calculated using the efficient techniques of large-scale mathematical programming.

1.3 A study using the PILOT model

Consideration of the above requirements has significantly influenced the structure of PILOT, a large-scale dynamic general equilibrium model of the U.S. economy. In order to take full advantage of engineering analysis as a basis for defining new or hypothetical technological alternatives, the production sector is modeled using the proven techniques of activity analysis (or linear process modeling). The general equilibrium framework integrates this representation of production with a system of smooth consumer demand functions. Solutions of the model provide a coherent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions in the context of technological change. In particular, the model can be used to assess the effects of different time paths of availability and/or technical characteristics of new technologies. A more detailed description of the PILOT model is contained in Section 3.

The present study employs the unique capabilities of PILOT to assess important differences between a "high-tech" and a "low-tech" economy, in terms of aggregate and sectoral patterns of growth, employment, and energy use over the next 25 years. While we may reasonably expect the direct effects of high technology to be labor-saving and somewhat energy-saving (though perhaps more electricity intensive), the indirect effects of higher economic growth, different import-export patterns, and different rates of growth in the various economic sectors are likely to be more important in determining overall patterns. An integrated, technology-oriented model such as PILOT can be profitably employed to evaluate the net effects of the whole array of economic forces at work. A broadly focused study of alternative energy/economic futures can provide a valuable perspective on general trends and magnitudes which would not be available from a more issue-specific analysis.

To this end we have developed a slate of four model scenarios designed to isolate a pure effect of delays in the availability of new technology. One scenario is designated as a base case, and each of three delay scenarios progressively subjects more industry groups or technologies to a delay. The first focuses on information processing technologies in the service industries and government. The second extends the delays to the manufacturing sectors, with a primary emphasis on electronics-related automation. The final delay scenario indirectly delays technologies which have no explicit representation in the model by reducing assumed rates of productivity growth in the industries using these technologies. For purposes of the scenario comparison, the cause of the delays in technology availability is not important. Any number of technical or economic factors, external to PILOT, could delay the introduction dates hypothesized in the base case. The usefulness of PILOT is not in modeling how and why technical advances are made but in assessing the potential utilization of new technologies and the associated effects on the economy as a whole.

1.4 Outline of the presentation

The balance of this report is organized as follows. In Section 2 we present the key assumptions and mathematical framework of the class of computable general equilibrium models addressed in this research. In Section 3 we focus on the PILOT model and describe its key components and overall structure. The overview material at the beginnings of these sections is intended to provide an adequate background for reading of the subsequent material. Section 4 contains a description of the model input assumptions that characterize the four scenarios of technological change. It also includes a discussion of how various structural features of the PILOT model can be expected to affect the results of the scenario analysis. Finally, Section 5 addresses the results of the modeling exercise, comparing trends in important economic and energy-related variables and examining the underlying economic and technological forces which account for the observed differences in economic performance across the four scenarios.

2

FUNCTIONAL FORMS FOR LARGE-SCALE CGE MODELS

In this section we present important simplifying assumptions about the nature of consumer preferences and production possibility sets. If a general equilibrium model satisfies these assumptions, then computing solutions to it will be practical even when the model is quite large. The overview subsection is non-technical and is intended to provide adequate background on these assumptions for reading the later sections of this paper. The development in the remaining subsections is mathematical, and the material may be omitted without loss of continuity by readers who are not interested in the details of the mathematical development.

2.1 Overview

We have already mentioned the value of using activity analysis as a framework for representing the production sector of the economy. This allows us to use engineering analysis as a basis for defining new or hypothetical technological alternatives. By adjoining an activity analysis model of production to a set of smooth algebraic functions representing aggregate consumer demand, a special and well-studied class of economic equilibrium systems can be constructed. The essential attributes of a competitive equilibrium solution in this case are as follows:

- (a) the demand for all commodities must be less than or equal to supply;
- (b) excess supply of any commodity implies a zero price for that commodity;
- (c) the net present value of each production activity must be nonpositive;
- (d) only production activities with zero net present value can be operated.

With respect to (c) and (d), a normal rate of return is allowed; only profits in excess of this rate (called economic profits) are eliminated at equilibrium.

For general nonlinear demand functions, the above conditions define a special case of the so-called nonlinear complementarity problem. Model variables include both production and consumption activities and commodity prices. A feasible solution, or choice of activities and prices, corresponds to satisfaction of conditions (a) and (c) above. An equilibrium solution is a feasible solution which furthermore satisfies the complementarity conditions (b) and (d).

Unfortunately, even for this elegant problem structure, solving a truly large-scale model with general nonlinear demand functions remains beyond the reach of current solution algorithms. If the richness of representation of the production sector is to be maintained, further simplifying assumptions must be made in terms of selecting a more restricted class of demand functions. In particular, we restrict our attention to the class of so-called *integrable* aggregate demand functions, that is, functions which could be derived from the optimality conditions for maximizing a known utility function. (A utility function is a mathematical construct used to represent a consumer's preferences among different commodities in terms of a single measure called utility.)

In developing and justifying a system of integrable demand functions for a dynamic general equilibrium model, two aspects of consumer demand are of primary importance: separability across time and states of nature, and the correlation between preferences and consumption expenditures in the population. The objective of the detailed analysis of Section 2.5 is to derive a formulation for consumer demand which allows a model to treat aggregate demand at a point in time or at a state of nature as a function of aggregate expenditures and the prices of consumed goods at that time/state, *independent* of the distribution of expenditures across the population and independent of prices or expenditures at other points in time or other states of nature.

The important implication of specifying an integrable system is that, in this case, a general equilibrium solution can be computed by maximizing the associated aggregate utility as a function of consumption levels subject to the activity analysis production constraints. The feasibility and optimality conditions for this mathematical program are precisely the equilibrium conditions (a) through (d). The integrable model structure thus acquires a significant computational advantage in that well-developed techniques of large-scale mathematical programming can be applied to solving the equilibrium problem.

2.2 The Arrow-Debreu model

The starting point for a general equilibrium model is the theory of Arrow and Debreu, as found in Debreu [1959], for example. This part of the paper sets out the notation for the model and then briefly gives the mathematical conditions defining an equilibrium. For reasons of convenience, the partition of commodities will be taken to be in time, as denoted by subscript and superscript t . None of the analysis would be affected if uncertainty were included and the partition of commodities were assumed to address states of nature as well as time. So as to keep the analysis in finite dimensions, we address a finite number of time periods $(1, \dots, T)$, with a finite number, l , of commodities traded in each period.

There are a finite number of consumers, indexed by $i \in N$. Each consumer has an initial endowment of commodities in each period, (w_1^i, \dots, w_T^i) , and a utility function, $u^i(x_1, \dots, x_T)$, which takes as its argument the consumption in each period. Let the feasible consumption

set for each consumer be the nonnegative orthant.

There are also a finite number of producers, indexed by $j \in M$. Each producer has a production possibility set $Y^j \subset \mathbb{R}^{IT}$, giving the feasible production plans for the horizon of the model. A production plan will be denoted by $(y_1, \dots, y_T) \in Y^j$. Any profit earned by firm j is distributed among consumers, with consumer i receiving a share $\theta_{ij} \geq 0$.

An equilibrium in this model is a price vector $p = (p_1, \dots, p_T) \in \mathbb{R}_+^{IT}$, a consumption plan for each consumer $\xi^i = (\xi_1^i, \dots, \xi_T^i)$, and a production plan for each producer $\eta^j = (\eta_1^j, \dots, \eta_T^j)$ which satisfy the following conditions:

$$\xi^i \in \arg \max_{x \geq 0} \left\{ u^i(x) \text{ s. t. } \sum_t p_t x_t \leq \sum_t p_t w_t^i + \sum_j \theta_{ij} \left[\sum_t p_t \eta_t^j \right] \right\} \quad (1)$$

$$\eta^j \in \arg \max_{y \in Y^j} \left\{ \sum_t p_t y_t \right\} \quad (2)$$

$$\sum_i [\xi_t^i - w_t^i] - \sum_j \eta_t^j \leq 0, \quad \text{complementary with } p_t \quad t = 1, \dots, T. \quad (3)$$

Condition (1) represents utility maximization for each consumer, subject to a budget constraint determined by the market value of initial endowments and the consumer's share in the net profits of all production plans. Condition (2) reflects profit maximization by each producer. The inequalities in (3) are the market clearing conditions, requiring for each commodity that the aggregate of the net demands of all consumers be no greater than the aggregate of the net outputs of all production plans. Complementarity with p_t means that any commodity in excess supply must have a zero price, and a commodity can have a positive price only if demand exactly equals supply.

Under suitable conditions an equilibrium is known to exist, so for the rest of this discussion, (p, ξ, η) will refer to a particular equilibrium for this Arrow-Debreu economy.

2.3 Activity analysis production

Many authors have found that linear activity analysis production is convenient for both theoretical and empirical analysis; see Scarf [1967] for an early treatment and Ginsburgh and Waelbroeck [1981] for an extensive discussion. In this context, we choose to represent each firm's production set by a polyhedral cone. When there are limits to the scale of a production process, these limits can be represented by constraining the supplies of some primary input commodities which are included in the endowments of the owners of the firm. This formulation guarantees that every firm will earn exactly zero profit in equilibrium — any income will be imputed to the primary commodities which the firm uses as inputs. Thus, the term representing firm profits can be dropped from the consumer budget constraint in condition (1).

In this activity analysis framework, let c_t^i represent the supply of primary commodities owned by consumer i . These commodities are not consumed and do not enter into his utility function, so without loss of generality, we can assume that he always sells his entire endowment. Thus, the supply of primary commodities in the market in each period t can be denoted by $k_t = \sum_i c_t^i$. The prices of these primary commodities will be denoted by q_t . By introducing additional commodities as necessary, we can also assume, without loss of generality, that the consumer has no endowment of the commodities he does consume. Thus, the maximization problem of consumer i , equation (1), becomes

$$\xi^i \in \arg \max_{x \geq 0} \left\{ u^i(x) \text{ s. t. } \sum_t p_t x_t \leq \sum_t q_t c_t^i \right\}. \quad (4)$$

The fact that the production possibilities set of each firm is a convex set means that the aggregate production possibilities set of all firms together is also convex. It also follows that the sum of the profit-maximizing production plans for the individual firms is a profit-maximizing production plan for the aggregate production possibility set and *vice versa*. The aggregate production possibility set is also a cone, so aggregate production can be represented by maximizing profit over some cone, given prices for outputs and primary commodity inputs. If we denote an equilibrium aggregate production plan by $\eta = (\eta_1, \dots, \eta_T)$, and the input of primary commodities in such a plan by $\rho = (\rho_1, \dots, \rho_T)$, then the collection of firm problems in equation (2) can be replaced by the following aggregate maximization problem:

$$\begin{aligned} (\eta, \rho) \in \arg \max_{(y, r)} & \sum_t [p_t y_t - q_t r_t] \\ \text{s. t.} & \quad y + A_1 z \leq 0 \\ & \quad -r + A_2 z \leq 0 \\ & \quad z \geq 0. \end{aligned} \quad (5)$$

The dimension of the vector z is the number of "production processes" in the economy. The dynamic structure of production is defined through the matrices A_1 and A_2 . The ability to represent production in an aggregate way like this is useful, since treating individual firms in a model of an advanced economy would be impractical.

In this model which includes primary commodities and in which consumers have no endowments of the commodities they consume, the market clearing conditions (3) are replaced by

$$\begin{aligned} \sum_i \xi_t^i - \eta_t &\leq 0 \quad \text{complementary with } p_t \quad t = 1, \dots, T \\ \rho_t - k_t &\leq 0 \quad \text{complementary with } q_t \quad t = 1, \dots, T. \end{aligned} \quad (6)$$

A general equilibrium model with activity analysis production fits within the standard Arrow-Debreu framework, thus implying the existence of an equilibrium (p, q, ξ, η, ρ) .

2.4 Separable utility

Separability in the context of consumer demand is a property of utility functions which enables us to compute demand at one point in time on the basis of prices and expenditures at that time, without reference to prices or expenditures in other periods. Suppose all the individuals in the economy solve utility maximization problems of the following form:

$$\begin{aligned} (\xi_1^i, \dots, \xi_T^i) \in \arg \max_{(x_1, \dots, x_T) \geq 0} & v^i(\bar{u}_1^i(x_1), \dots, \bar{u}_T^i(x_T)) \\ \text{s. t.} & \sum_t p_t x_t \leq \sum_t q_t c_t^i. \end{aligned}$$

If the demands chosen result in total expenditures in each period of $\zeta_t^i = p_t \xi_t^i$, then these demands must have the property that

$$\xi_t^i \in \arg \max_{x_t \geq 0} \left\{ \bar{u}_t^i(x_t) \text{ s. t. } p_t x_t \leq \zeta_t^i \right\}. \quad (7)$$

Given total expenditures ζ_t^i , demand in period t is a function $\xi_t^i(p_t, \zeta_t^i)$ independent of expenditures and prices in other periods.

Separability of the utility function for consumer i also gives an easy way to calculate the distribution of his expenditures over time. If for any pattern of expenditures $h = (h_1, \dots, h_T)$ and corresponding prices p , we define a function γ^i as follows:

$$\gamma^i(h, p) = v^i \left(\left(\max_{x_t \geq 0} \{ \bar{u}_t^i(x_t) \text{ s. t. } p_t x_t \leq h_t \} \right)_{t=1, \dots, T} \right), \quad (8)$$

then the equilibrium values $\zeta^i = (\zeta_1^i, \dots, \zeta_T^i)$ will be maximizers:

$$\zeta^i \in \arg \max_h \left\{ \gamma^i(h, p) \text{ s. t. } \sum_t h_t \leq \sum_t q_t c_t^i \right\}. \quad (9)$$

Equations (7) and (9) constitute a sufficient model of the behavior of consumer i , equation (7) giving his behavior at each point in time as a function of prices at that time and expenditures allocated for that time, ζ_t^i , and equation (9) giving the distribution of expenditures over time, ζ^i .

It has long been recognized, in the context of a standard model like the one discussed here, that if markets are complete and there are no asymmetries of information, then a standard Arrow-Debreu equilibrium can be achieved via a simplified market structure (see Arrow [1964] for an early exposition). The original equilibrium, which is usually thought of as being defined in terms of futures contracts for commodities, can also be implemented via a smaller set of markets: markets for securities (one is needed for each period) and a sequence of spot markets for commodities in each period. Suppose we write \bar{p}_t and \bar{q}_t for the spot market prices in period t , normalized in some convenient way, and define β_t by $\bar{p}_t = \beta_t^{-1} p_t$.

β_t can be interpreted as the selling price at the beginning of the model of a security which pays one currency unit in period t . As we shall show, the β_t can also be interpreted as discount factors, either from the point of view of producers or consumers.

We can define $\tilde{\zeta}_t^i$ as consumer i expenditures in the spot market at period t , and equation (9) is then equivalent to

$$\tilde{\zeta}_t^i \in \arg \max_{\tilde{h}} \left\{ \gamma^i(\tilde{h}, \tilde{p}) \text{ s. t. } \sum_t \beta_t \tilde{h}_t \leq \sum_t \beta_t \tilde{q}_t r_t^i \right\}. \quad (10)$$

In this context, the producer objective function from equation (5) becomes

$$\sum_t \beta_t [\tilde{p}_t y_t - \tilde{q}_t r_t], \quad (11)$$

which is the present value of the stream of spot market profits, discounted using the factors β_t . In this scheme, an equilibrium is defined as prices \tilde{p}_t and \tilde{q}_t and a discount factor β_t for each period, consumer demands ξ_t^i and expenditures $\tilde{\zeta}_t^i$, and producer net supplies (η, ρ) with the following properties:

- (1) consumer demands satisfy the within-period optimization conditions, equation (7), with respect to the prices \tilde{p}_t and expenditures $\tilde{\zeta}_t^i$;
- (2) the expenditures $\tilde{\zeta}_t^i$ satisfy the intertemporal optimization conditions, equation (10);
- (3) the producer net supplies maximize discounted profit, equation (11), subject to the feasibility constraints in equation (5); and
- (4) all markets clear, equation (6).

The numbers β_t are also equivalent to discount factors or interest rates in the usual sense, that is, they represent the marginal rate of substitution of income between periods for every consumer.

Proposition. Given an Arrow-Debreu equilibrium (p, q, ξ, η, ρ) and the corresponding functions γ^i defined in equation (8), and given a rule for normalizing spot market prices $\tilde{p}_t = \beta_t^{-1} p_t$, the spot market expenditures $\tilde{\zeta}_t^i$ for each i and for each t obey

$$\frac{\partial \gamma^i}{\partial h_t} \bigg|_{\tilde{\zeta}^i, \tilde{p}} = \frac{\beta_t}{\beta_1}. \quad (12)$$

It is quite convenient to separate the consumer's decisions in this way. It is easy to imagine that the within-period consumer demand function could be estimated econometrically, using

time-series data on prices, expenditures, and demand. Indeed, this is what we have done for PILOT. (Of course, we still have to pass from the demand of an individual consumer to aggregate demand, in order to be able to use the aggregate data which is available. Aggregation is the subject of the next subsection.) Parameterizing the intertemporal preferences represented by the function γ^i is much more difficult, however. In any real economy, saving is performed by a wide variety of institutions, and it is often mandated by laws or other considerations apart from the optimization of the actual consumers. As a consequence of this difficulty, we have chosen to treat intertemporal preferences in a rather arbitrary way in PILOT, as discussed in Section 2.6.

2.5 Aggregate demand functions

In the context of the standard general equilibrium model, it is possible to calculate aggregate consumer demand as a function of all prices in the market. The prices determine the income of each consumer and thus his budget set and utility-maximizing demand. These individual demands can then be summed to derive aggregate demand. In a computational representation of an actual economy, this calculation is simply impossible. It would require data on the endowments and utility functions of every agent, and even if this data were available, the computations would be far too lengthy to be actually performed. As a result, in a large-scale computational model it is desirable to be able to treat aggregate demand as a function, preferably in closed form, of the prices for the goods which the consumers buy and of aggregate income or consumption expenditures. It is also important that this function have a representation in terms of the maximum, subject to a budget constraint, of a concave function. If this property (called integrability) is satisfied, the model can be solved as an optimization problem, in a form for which computational methods are available that can solve problems with thousands of variables. If this property is absent, then computation of an equilibrium becomes much more difficult. Stone [1988] analyzes algorithms for solving general equilibrium problems, and finds that problems of the size we need can at present be routinely solved only if they can be represented in an optimization form.

It has been shown that an integrable aggregate demand function exists only under extremely restrictive assumptions. These assumptions essentially require that every agent have a demand function which is linear in expenditures and which is the same as that of every other agent, except possibly for the addition of a term which depends on price but not on expenditures. In other words, an aggregate demand function exists only if every agent has linear Engel curves at every price and, moreover, only if they are parallel to the Engel curves of all other agents at that price. For an exposition, see Gorman [1953].

This result has recently been extended by Jorgenson *et al.* [1982] to allow agent demand to depend on some attributes of the agent which are independent of prices and income. This gives rise to an aggregate demand function which depends not just on aggregate income,

but on a larger class of symmetric statistics of the income distribution. This extension does not help in a large-scale general equilibrium model, however, because calculating statistics of the income distribution requires exactly the information about that distribution which is impractical to obtain.

One way out of this dilemma is to change slightly the interpretation of the formal model of consumer behavior which has been presented above. Imagine a model in which the consumption sector is comprised not of N specific consumers with given utility functions and endowments, but rather of N consumers drawn at random from an urn containing a population of "prospective consumers" characterized by a *distribution* of utility functions and endowments. In this model, our concern is not with the exact value of the sum of all individual demand functions, but with the expected value of that sum, where the expectation is taken with respect to the statistical distribution of utility functions and endowments for the population in the urn. Using this expected value may be a reasonable model choice if, for example, regression is used to estimate the aggregate demand function, for then the expected value is all that is estimated anyway. Since we have estimated an aggregate demand function for the PILOT model by regression, this is a reasonable interpretation in the context of that particular model. Another way to interpret the operation of taking the expected value of aggregate demand is that this expectation produces the exact aggregate demand (with probability one) if each consumer i is not an individual but rather an aggregation of a continuum of identically distributed individuals.

Whatever the underlying justification for using the expected value of aggregate demand in a model, the result can be quite convenient for analytical and computational purposes. In certain cases, it turns out that this expected value function is much better behaved than the actual aggregate demand function. A mathematical analysis of the expected value of aggregate demand in a somewhat simpler setting than the one discussed here can be found in Shapiro [1977], who also points out that his analysis would generalize to the one presented here. Shapiro does not attempt to provide any explanation for why the expected value of aggregate demand might be interesting, but of course, the mathematical analysis can be used independent of any interpretation.

In related work on the statistical relationship between expenditures, preferences, and demand, Hildenbrand [1983] has focussed on the distribution of income, rather than of preferences. He derives conditions on this distribution under which aggregate demand obeys the weak axiom of revealed preference. His result has been extended in Grandmont [1987] to consider restrictions on the joint distribution of preferences and expenditures which include a condition related to the shifted homotheticity we impose below. Finding aggregate demand which obeys the weak axiom may also prove to be convenient from a computational point of view. Research such as that surveyed by Nagurney [1987], for example, suggests that there are computational methods which can handle large models in which aggregate demand is a monotone function, a condition which is somewhat stronger than the weak

axiom. Combining the ideas of Hildenbrand and Grandmont with those reported here is a promising avenue for future research in computational general equilibrium models.

In order to analyze the expected value of aggregate consumption, we must characterize the distribution over which the expectation is to be taken. Accordingly, we imagine that the population consists of N consumers, each of whom has preferences distributed according to some probability distribution. We make two assumptions, the first about preferences and the second about the relationship between preferences and expenditures. Preferences are assumed to be strictly convex and homothetic with respect to some point, not necessarily the origin (shifted homothetic). If preferences satisfy these assumptions, then the demand of each agent i for consumption commodities is a single-valued function of prices and expenditures. Moreover, at given prices the function is linear in expenditures. Thus, the demand of agent i at prices p and expenditures h^i , when his preferences are a function of some parameter ω in an abstract probability space Ω , is

$$\xi^i(p, h^i, \omega) = a^i(p, \omega) + h^i b^i(p, \omega). \quad (13)$$

In addition to satisfying this domain assumption, the distribution of preferences is assumed to be independent of total expenditures or income.

With demand functions that are linear in expenditures and distributed independently of expenditures, the expected value of aggregate demand, Ξ , can be computed by just adding the values from equation (13) and integrating with respect to the distribution of ω :

$$\begin{aligned} E[\Xi(p, (h^i)_{i \in N}, \omega)] &= E \sum_i [a^i(p, \omega) + h^i b^i(p, \omega)] \\ &= \sum_i E a^i(p, \omega) + \sum_i E[h^i b^i(p, \omega)] \\ &= N E[a(p, \omega)] + E[b(p, \omega)] \sum_i h^i. \end{aligned} \quad (14)$$

Henceforth, we can suppress the argument ω . Now the expected value of *per capita* demand, ξ , can be found by dividing $E[\Xi]$ in equation (14) by the size of the population. Writing h with no superscript for *per capita* expenditures, this yields:

$$\xi(p, h) = E a(p) + h E b(p). \quad (15)$$

We would like to find restrictions on the distribution of preferences such that this expected value of *per capita* demand can be derived from the optimality conditions for maximizing a concave utility function.

The conditions under which a demand function represents maximizing behavior for some concave utility function are well known. Necessary and sufficient conditions were derived by Hurwicz and Uzawa [1971] in terms of the Slutsky substitution matrix S , defined by $S = \frac{\partial \xi}{\partial p} + \frac{\partial \xi}{\partial h} \xi'$. First, we observe that the function ξ is homogeneous of degree zero and

satisfies Walras' Law with equality, $p'\xi(p, h) = h$, since this is true for each individual demand function. Given these properties, the demand function ξ can be derived from maximizing some concave utility function $\nu(x)$ subject to a budget constraint, that is

$$\xi(p, h) = \arg \max_{x \geq 0} \{ \nu(x) \text{ s.t. } p'x \leq h \},$$

if and only if the matrix S is symmetric and negative semidefinite. In our case, assuming that certain regularity conditions are met, the matrix is given by

$$S = E \left[\frac{\partial a}{\partial p} \right] + hE \left[\frac{\partial b}{\partial p} \right] + Eb[Ea' + hEb']. \quad (16)$$

In studying this matrix, it is useful to compute the Slutsky matrix for an individual agent and look at its expected value:

$$ES^i = E \left[\frac{\partial a}{\partial p} \right] + hE \left[\frac{\partial b}{\partial p} \right] + E[ba'] + hE[bb']. \quad (17)$$

We find that, by combining equations (16) and (17), the Slutsky matrix for the expected *per capita* demand function ξ can be written as

$$S = ES^i - h \text{Var}[b] - \text{Cov}[b, a']. \quad (18)$$

The first term on the right-hand side is the expected value of a variable which is everywhere a symmetric and negative semidefinite matrix; hence, it is also symmetric and negative semidefinite. The term $-h \text{Var}[b]$ is symmetric and negative semidefinite. Thus, the integrability of the function ξ depends on the last term in equation (18). If $-\text{Cov}[b, a']$ is symmetric, then so is S . If in addition it is negative semidefinite or, if not, is sufficiently "small" relative to the other terms, then ξ is integrable. If these conditions are not satisfied, then ξ is not integrable.

The term $-\text{Cov}[b, a']$ could be conveniently ignored if a and b could be taken to be independent. Unfortunately, this is impossible. Given Walras' Law, for any p and h it must be true that $p'[a(p, \omega) + hb(p, \omega)] = h$ for all values of ω . Consequently, a and b cannot be independent. Nonetheless, there are functional forms and distributions of (nonidentical) preferences for which the matrix S is symmetric and negative semidefinite. One such case is described in the next subsection, which addresses the development of the expected *per capita* demand function used in the PILOT model.

2.6 The functional form of PILOT

In order to specify a model which meets the restrictions suggested above, specific functional forms must be chosen for the within-period utility functions \tilde{u}^i and the inter-period utility

functions γ^i . Our analysis considers a within-period utility function for consumer i of the form

$$\bar{u}^i(x) = (s^i - x)' M^i (s^i - x). \quad (19)$$

Here, s^i is a vector and M^i is a negative definite matrix. Obviously, the unconstrained maximum is obtained at $x = s^i$, so s^i is assumed to be strictly positive (and indeed, in practical terms, "large" by comparison with the consumption levels which can possibly be achieved over the horizon of the model). If this function is maximized subject to the budget constraint $p'x \leq h^i$, where prices p and expenditures h^i are such that $h^i < p's^i$ and all components of x^i are strictly positive, then the first-order conditions for a maximum give the demand function

$$\xi^i(p, h^i) = s^i - \frac{p's^i - h^i}{p'H^i p} H^i p. \quad (20)$$

The matrix H^i in this equation is just the inverse of M^i from equation (19).

At every price and expenditure combination for which $h^i < p's^i$ and $\xi^i(p, h^i) > 0$ according to equation (20), demand is linear in expenditures and the Slutsky matrix S^i is negative semidefinite. In this range, then, the function above is in the form analyzed in the previous subsection. A long analysis, which is reported in Dantzig *et al.* [1988] and will not be repeated here, shows that if s^i and H^i are independent, then the requirement on the covariances in equation (18) can be met for a wide variety of distributions of H^i , thus yielding an expected *per capita* demand function that is integrable. These conditions are not, however, sufficient to determine the appropriate functional form for the function in (15) relative to individual demand functions of the form (20). In order to obtain a function with suitable properties that can be estimated econometrically, we have assumed that the expected *per capita* demand function can be adequately approximated by a function of the same form as that used for the individual demand functions in (20).

The actual institutions through which saving and investment behavior in the U.S. are determined are labyrinthine, and it is not obvious that the end result is necessarily "optimal" in the sense that it could be represented by optimizing behavior in a general equilibrium model. Our modeling objectives do not really require a precise simulation of the U.S. financial system, but we would like intertemporal decisions in the model to be made on the basis of criteria which are plausible approximations to the criteria that determine actual investment in plants and equipment. As a result of these considerations, we have chosen to treat saving in a rather stylized way in PILOT. Fortunately, experimentation with the model has suggested that the results are not very sensitive to the rate at which future returns are discounted, at least within a wide range of discount rates. We thus pick a discount factor, δ , and the full model is formulated as follows:

$$\max \sum_{t=1}^T \delta^{t-1} (s - x_t)' M (s - x_t) \quad (21)$$

$$\text{s. t.} \quad x_t - y_t \leq 0 \quad t = 1, \dots, T \quad (22)$$

$$r_t \leq k_t \quad t = 1, \dots, T \quad (23)$$

$$y + A_1 z \leq 0 \quad (24)$$

$$-r + A_2 z \leq 0 \quad (25)$$

$$x, y, z \geq 0.$$

With a negative definite matrix M , the first-order Kuhn-Tucker conditions are necessary and sufficient for a maximum.

Let us assume that there is a solution in which x and y are away from their lower bounds, and let us denote by p and q the dual prices on rows (22) and (23), respectively. In this case, since equations (24) and (25) are just the activity analysis representation of the production possibilities set and since the variables in these equations do not enter into the objective function, the values of y and z are the profit-maximizing production plan at the prices p and q . The first-order conditions on x_t imply that it is a maximizer of the within-period utility function at prices p_t and the allocated total expenditures for period t . The markets clear by virtue of equations (22) and (23), and complementarity with p and q is implied by the Kuhn-Tucker conditions. Finally, the intertemporal distribution of consumption expenditures, $\zeta_t = p_t x_t$, maximizes the function

$$b(h, p) = \sum_t \delta^{t-1} [(s - \xi(p_t, h_t))' M (s - \xi(p_t, h_t))],$$

subject to $\sum h_t \leq \sum q_t k_t$. (This follows from the fact that

$$s - \xi(p_t, h_t) = \frac{p'_t s - h_t}{p'_t H p_t} H p_t,$$

and some tedious algebra, which returns a representation of the original objective function.) Hence, a solution of the optimization problem above is an equilibrium for the corresponding general equilibrium model.

3

THE PILOT MODEL

Up to this point, we have basically characterized PILOT as a dynamic general equilibrium model which integrates an activity analysis representation of the production sector with a system of smooth consumer demand functions. In this section we identify the real-world activities and relationships which are represented in this general mathematical structure. The initial overview is designed to provide an adequate background for reading Sections 4 and 5, which discuss scenario design and the results of the scenario analysis. We also encourage reading of Section 3.6 on appropriate uses of the PILOT model. The remaining subsections describe the major components of PILOT in moderate detail. Readers interested in further details are referred to previous model documentation in Dantzig *et al.* [1981] and Dantzig *et al.* [1985].

3.1 Overview

PILOT's activity analysis representation of production goes beyond traditional fixed-coefficient input/output analysis by defining multiple columns for each sector representing alternative production technologies for new investments. The productive capital stock is vintaged and unmalleable once in place. Domestic industries compete with imports (whose prices are given exogenously) and face a downward-sloping export demand schedule (also exogenous). The exchange rate is determined endogenously. Final demand is represented via a government input/output sector, endogenous investment activity in all sectors, and consumer demand for 13 aggregate commodities. *Per capita* demand for 5 of these consumption aggregates is specified exogenously. Demand for the other 8 is a function of prices and income, modeled via an aggregate quadratic utility function (see Sections 2.1, 2.5 and 2.6 for the development and justification of this structure).

The energy-producing sectors of the economy as well as energy-use decisions in manufacturing and in residential and commercial buildings are represented via modular process models. The results and assumptions of more detailed energy models are frequently used to adjust model calibration and to apply appropriate constraints so as to obtain energy results consistent with those of the more detailed models.

PILOT directly represents economic activities and relations in each of nine periods of five years in length, covering the time horizon 1975-2015. A given activity representing a long-lived investment may have coefficients in the relations of many subsequent periods. It may also have coefficients in the relations of one or more previous periods to the extent that

the investment requires a substantial construction lead time. Since decisions to undertake these long-lived investments are made with perfect foresight, an equilibrium solution must be calculated simultaneously across all time periods. The resulting linearized dynamic model of production is rather large, amounting to some 2000 relations and 4800 variables. The matrix of activity analysis coefficients is unusually dense for an economic model of this size, containing some 75000 nonzero elements. Solving an equilibrium model with a production sector of this size is made practical only by invoking the simplifying assumptions and corresponding model structures developed in Section 2.

3.2 Aggregate input/output sectors

The sectoral aggregation scheme in PILOT encompasses 40 aggregate economic sectors, as defined in Table 1. These include 23 manufacturing sectors and 9 service sectors, selected with particular attention to isolating those industries that are likely to be most heavily affected by technological innovation relating to electronics and automation. Four of the aggregate sectors correspond to primary energy production and conversion activities, and have an expanded activity analysis representation which is described below. The nonenergy sectors are represented by import and export activities and by one or more production activities, each of which is modeled by input/output relations defining the flows of goods and services into and out of that sector per unit of activity. The historical benchmark for the input/output coefficients in the model is the 1977 Department of Commerce input/output table.

The modeling of production in PILOT implements an important enhancement over conventional input/output modeling by incorporating multiple columns for each sector, representing alternative technologies which could be adopted in the future. Many fundamental changes in the structure of the economy can be meaningfully represented in terms of changes in the input/output relations of one or more economic sectors. Structural changes which can be represented in this manner include the overall improvement in factor productivity which results from technological innovation and price-driven substitution among inputs to production.

Technical alternatives included in the model may have quite different motivations and direct effects on the nature of a production activity. Some are primarily labor-saving innovations, most notably factory and office automation. Others are primarily related to energy conservation, such as use of more efficient electric motors, more heat recovery or insulation, and Alcoa process aluminum production. Still others, such as Rapson process papermaking, steel minimills, or continuous casting of metals, represent complete alternative processing chains, with pervasive effects on productivity and all material flows.

A given alternative technique is represented in PILOT via a particular input/output activity, with a preoperation investment requirement and a time stream of output and operating

Table 1
ECONOMIC SECTORS OF THE PILOT MODEL

PILOT Sectors	BEA Sectors
1. agriculture	1-4
2. mining	5,6,9,10
3. construction	11,12
4. food and tobacco products	14,15
5. textiles, apparel, and leather	16-19,33,34
6. lumber and wood containers	20,21
7. paper and allied products	24,25
8. printing and publishing	26
9. chemicals and paints	27,30
10. plastics and synthetic materials	28
11. drugs, cleaning and toilet preparations	29
12. rubber and plastic products	32
13. stone, clay, and glass products	35,36
14. primary iron and steel	37
15. primary nonferrous metals	38
16. metal products	39-42
17. heavy machinery	43-46, 61
18. precision machinery	47,50,62,63
19. industrial machinery	48,49,53
20. electrical appliances	52,54
21. computers and office equipment	51
22. radio, TV, and communications equipment	56
23. electronic components	57
24. motor vehicles and equipment	59
25. aircraft and parts	60
26. miscellaneous manufacturing	13,22,23,55,58,64
27. transportation and warehousing	65
28. communication common carriers	66,67
29. trade	69
30. finance and insurance	70
31. real estate ¹	71
32. miscellaneous services	72,75,76,78,79 ²
33. business services	73
34. eating and drinking places	74
35. health, education, and social services	77
36. coal	7
37. crude oil and natural gas	8
38. petroleum refining	31
39. electric, gas and other utilities ³	68,78.02,79.02
40. residential housing	—

¹Excludes rental value of buildings and land

²Excludes 78.02, 79.02

³Includes government utilities

Separate rows for electricity, gas, and all other

inputs (labor, energy services, commercial building services, and commodities from other sectors). The model embodies a "putty-clay" formulation, in which, once a unit of capacity using a certain technique has been installed, that unit of capacity is restricted to using the chosen technique until it is retired. At equilibrium, an activity is utilized only if, at model-determined prices, the net present value of investment and the time stream of inputs and outputs is zero.

The available alternatives for a given sector may change over time, reflecting technological change, but in most sectors a choice of two or three alternatives is available for new investments in each time period from 1985 onward. We believe that endogenously determined combinations of the alternative input/output columns reasonably span the alternative structures the U.S. economy might assume over the next 20-25 years.

3.3 Energy supply sectors

Depletion of the U.S. stock of energy resources will be an important factor influencing conservation and technological choices in the future. PILOT represents, in physical terms, the increasing effort required to find and produce incremental units of oil, gas, coal, and uranium, as currently producing deposits become depleted and progressively more difficult deposits must be utilized. As a result of this depletion, in most model solutions the market prices of energy and energy-intensive commodities increase over time relative to those of other commodities. This motivates changes to more energy-efficient technologies by the various sectors in the model.

Production of oil and gas and of coal are treated similarly in PILOT. Exploration for oil and gas is characterized by a finding-rate curve, which links the amount of oil or gas found per foot drilled to cumulative drilling. Oil production is separated between primary and enhanced recovery, with different costs associated with each. The coal module divides the United States into two regions, East and West, because of the substantial differences in the coal mining industries in these regions. Within each region, operating costs, manpower requirements per ton of coal mined, and investment costs for opening new coal mines are an increasing function of cumulative coal production. Since other activities in PILOT are not regionalized, a simple time trend is specified to define the proportion of total coal demand occurring in each region.

To bridge raw energy supplies and processed energy demands, PILOT incorporates straightforward process representations of electricity generation, natural gas processing, petroleum refining, and gas and electricity transmission. The usual complement of nuclear, fossil fuel, hydro, and unconventional electric power plants is provided. There is also some detail on the nuclear fuel cycle. Petroleum refining is greatly simplified, considering only homogeneous crude oil and an aggregate of all refined oil products. Such a simplification does not seriously bias long-run aggregate results.

3.4 Energy end use

Consumption of energy for most industrial, commercial, and residential uses, as well as for personal automobile transportation, is modeled by an activity analysis representation of the end-use conversion and conservation processes involved. In the manufacturing sector, consumption of various end-use services (e.g., steam, metal heating) is determined on the basis of output levels and technology choices in those sectors of the economy. These services are supplied by stocks of various alternative conversion devices distinguished by efficiency, fuel use, and other physical characteristics. The demand for commercial building space is determined as a function of output levels in the commercial sectors of the economy, while the associated demand for energy end-use services (e.g., space heat) is determined as a function of the building stock, which is differentiated by type, efficiency level, and location. These services are supplied by stocks of conversion devices, again defined in terms of fuel type, efficiency, and operating characteristics. The residential sector is modeled in a manner similar to the commercial sector, but with less detail. Finally, automobile travel for final consumers is treated as an energy end-use service, with a variety of automobiles, at varying fuel efficiency levels, available to supply this service. A substitution relationship is also defined to represent consumer choice between large and small automobiles. Transportation uses of energy in the rest of the economy are modeled through the input/output relations for each economic sector, and efficiency is assumed to improve at an exogenously specified rate.

3.5 Final demand

Final demands for goods and services in consumption, investment, and government activity are the driving forces behind the economy. Consumer use of each commodity in PILOT is determined on the basis of price-sensitive demand functions for 8 aggregate commodities: housing, household operation, transportation, 2 recreation aggregates, clothing, personal care services, and personal care supplies. *Per capita* consumption of food, health care services, personal business services, private education, and foreign travel are specified exogenously. This commodity aggregation scheme reflects a blend of common sense and data analysis. The price-sensitive demand functions are estimated econometrically using a flexible functional form which embodies both own- and cross-price effects (see Section 2.6 for the mathematical specification). Demand for each commodity resulting from investment activity is determined on the basis of the rate of capacity expansion taking place in each sector. Capacity expansion costs for each investment activity are first aggregated into a number of general expenditure types, e.g., buildings, industrial equipment, and computers and office equipment. A different fixed allocation of expenditures among commodities is then made for each aggregate. Finally, the government demands various commodities in fixed proportion to total government purchases of goods and services. The level of government expenditures

is proportional to the levels of production and other final demand activities, using constants of proportionality which may be interpreted as tax rates.

3.6 Appropriate use of PILOT

We do not consider PILOT to be a forecasting model in the sense in which this term is frequently misused. PILOT results, like those of any model, can be viewed as forecasts conditional upon the whole array of behavioral and technological assumptions inherent in model structure and parameterization. This conditioning is all too frequently overlooked or misunderstood in discussions and comparisons of model results. There are two reasons in particular why we do not deem it appropriate to view PILOT results as point forecasts. First, a given model scenario requires numerous exogenous assumptions about highly uncertain real-world magnitudes, such as availability of new technology, world oil prices, and import/export market conditions. This inherent uncertainty in model inputs is naturally inherited by model results, which cannot then be interpreted as unconditional forecasts. The proper mode of analysis is to assess the sensitivity of model results to important and uncertain input assumptions, and thereby ascertain whether particular results appear to be robust across various alternative futures.

Second, PILOT is not designed to model the short-term issues of the transition from a benchmark state to a long-term trajectory, but rather to capture the major economic and technological forces that determine the long-term trajectory. Because of departures in the real world from such paradigms as perfect competition and perfect look-ahead, we cannot expect the economy to behave as smoothly or efficiently through a transition as does a model like PILOT. So, again, a point forecast interpretation is inappropriate. What we can expect, however, is that the combination in PILOT of rigorous model structure and credible input data helps to ensure that differences across model scenarios truly reflect basic economic movements. That is, the model can be reliably used to obtain consistent comparative analyses of alternative long-run trajectories based on systematic alterations of key input assumptions.

With respect to policy analysis, PILOT is best suited to addressing direct controls (such as import quotas or fuel use restrictions) and relatively simple output-based taxation (for example, import duties). Its ability to directly represent more complicated taxation schemes is limited, although these can sometimes be represented adequately by indirect means. The model is not designed to study very sector-specific or region-specific issues, but rather to synthesize the results of microeconomic analyses of such issues, arising from more detailed and narrowly focused models. A wealth of detailed information is available from PILOT scenarios, including final consumption levels by commodity; industrial output, employment, and productivity levels by industry; import/export balances by commodity; and fuel-specific energy production and end-use patterns.

4

STRUCTURE OF THE STUDY

We describe the construction of four model scenarios designed to isolate a pure effect of delays in the availability of new technology. For convenience, we shall refer to one scenario as the Baseline and to the others collectively as the delay cases. In this section we discuss three separate aspects of the scenario design. First, we describe important assumptions about labor savings resulting from new electronics-intensive production techniques. These assumptions underly many of the production alternatives available in the Baseline scenario, and the delay cases are intended to assess the effects of delaying the hypothesized availability dates for the new technologies. The exact nature of the delays represented is then described in Section 4.2. In Section 4.3 we discuss some key model assumptions and structures which do not vary across scenarios but which can be expected to significantly condition scenario results.

4.1 Labor-saving automation technologies

Over the time horizon captured in PILOT, automation to a large extent will involve substituting electronics-intensive modes of production for labor-intensive ones. The rate at which such substitution occurs is driven by the rate at which price/performance improvements take place in electronic equipment (which has been quite rapid in the recent past). In particular, future price/performance improvements in computers and related components are a critical determinant of overall system costs for automation in both the factory and the office. Here, we have assumed improvements that average out to about twenty percent per year (compounded), a value which is in line with historical experience. The conventional wisdom is that it is probably reasonable to expect progress at a rate equal to the historical one at least until the end of this century. We have not considered improvements beyond this level, although in the model the efficiency of the capital stock continues to improve beyond 2000 because of the retirement of older vintages of equipment.

Several factory and office automation techniques are specified as production alternatives for each sector in the model. We will briefly indicate the magnitude of the efficiency gains of the technologies available at the end of the model over those of the late 1970's and early 1980's, describing the reductions they achieve in labor demand per unit of output. Automation also affects capital costs and other inputs in the model, but labor savings are the most important consideration. Factory and office automation can be expected to affect requirements for labor differently, depending on both the sector involved and the type of labor (professionals will be affected differently from assembly line operatives, for example). The sectors in the

model can be grouped into four general classes: processing industries, assembly industries, services, and a group of heterogeneous sectors that are treated idiosyncratically, including the trade, transportation, and construction sectors. Labor requirements for each production technology are calculated separately for eight occupational groups: professional/technical, managerial, clerical, sales, craft, operative, service, and laborers.

It is important to keep in mind that the discussion of efficiency gains in this section is not about scenario results but about background assumptions on the characteristics of hypothetical individual production techniques. In each scenario these techniques become available at specified future dates, and the extent to which any technique is utilized in the general equilibrium solution is the associated scenario result.

We have a moderate degree of confidence in the underlying assumptions about labor-saving technology. The model coefficients are calibrated to the 1977 benchmark input/output table, and the coefficients have been picked to approximately calibrate to experience in the actual economy from 1975 to 1985. It seems that the optimistic assessments in the Baseline scenario are somewhat better than this historical experience, while the pessimistic ones in the delay cases range from about equal to historical experience to somewhat worse. Consequently, the scenarios can be interpreted as one particular view of how to escape from the productivity slowdown of the 1970's.

4.1.1 Labor-savings

The occupations for which automation produces the smallest labor savings are in the professional/technical category.¹ In most non-service sectors the most efficient technique defined saves only 25% of the labor requirement in this category, and in the service sectors only 15% is saved. At the other end of the scale are factory workers. In the most efficient techniques in the assembly manufacturing sectors, the labor input requirement of craft labor is reduced by 80%, of operatives by 90%, and of laborers by 95%. These numbers amount to an assumption that, by early in the next century, it should be possible to build almost completely unmanned assembly plants for autos, machinery, and the like. (Remember that these labor savings are associated with new facilities. It will be well into the next century before the capital stock has turned over to such an extent that most plants attain this level of efficiency.)

Savings of managerial labor input requirements are about the same as those for professionals in most sectors (25%), but these savings increase to 45% for those sectors in which the number of production workers who have to be supervised is falling rapidly. Labor requirements for clerical and for sales workers in most sectors are reduced by about 35% in the most efficient techniques. One exception is the financial services sector, for which savings

¹ Actually, this is true only among those occupations for which there is any labor saving at all; we assume no labor savings due to automation in service occupations.

in clerical and sales occupations is 75%. Another exception is the retail and wholesale trade sector, in which 40% savings are specified for comparable vintage technology. In addition, the trade sector has a new technique available in 2015 (in the Baseline scenario only) which entails 50% savings of clerical and sales workers. Finally, no labor savings among service workers are assumed to take place as a result of factory and office automation.

4.1.2 Usage of electronic equipment

The inputs of electronic equipment required in order to achieve these labor savings are substantial. We focus here on robots and on computers and office equipment. The general rule assumed for substitution of robotic assembly is that one robot is needed per each five to ten workers in reduced labor demand. This ratio differs from the conventional wisdom, since recent experience seems to indicate that a substantial proportion of the labor savings are due not to having robots do tasks which human workers did previously, but instead are due to being able to eliminate some of the tasks completely. As to computers and office equipment, the most efficient new technology in most sectors requires buying a new computer every four years for each professional/technical, managerial, clerical and sales worker. We assume that by 2000, a computer suitable for a professional or managerial worker would have cost \$1 million (at 1977 prices and using 1977 technology), the one for the clerical worker would have cost \$0.5 million, and the point of sales terminal for each sales worker would have cost \$0.2 million. Following our assumed price/performance rule for technological improvements in computers, these values are equivalent to about \$10,000, \$5000, and \$2000, respectively, at prices in the early 21st century (expressed in 1977 dollars). These numbers seem, if anything, quite conservative. The new generation of 32-bit workstations have as much CPU capacity as a 1980-era VAX minicomputer, although they do not yet have as much mass storage capacity. The 1980-era VAX cost nearly a million dollars at the time, while the workstations sell for not much more than \$10,000 now. Workstations this powerful are not on every desk yet, but they may easily be so in a few years. Indeed, if anything prevents such powerful workstations from being ubiquitous by the year 2000, it is likely to be a lack of software not hardware. The question is not whether these computers can be built, but whether people can figure out what to do with them.

4.2 Three technology delay scenarios

We designate one scenario as a Baseline, relative to which three delay cases progressively subject more industries or technologies to a delay in availability. An important exception to these delays is advanced processing technology in the electronics manufacturing sectors, which is allowed in all scenarios to progress at the Baseline rate. This reflects a scenario design assumption that the U.S. remains competitive in terms of *producing* electronics technology but falls behind in the delay cases with respect to *utilizing* the advanced electronics

technology in producing other goods and services.

The first delay case focuses on the services industries and government and will be called the Delay Services case. This scenario delays labor-saving technologies making use of advanced electronics and information processing. No other sectors or technologies are affected. We isolate such technologies in the service sectors for two reasons. First, we believe the estimates of opportunities for productivity growth in services to be more conjectural than those for manufacturing. Second, we wish to be able to compare the effects of delaying new service-sector technologies to those of delaying manufacturing technologies.

The next delay case, the Delay All case, subsumes the delays of the Delay Services case and also delays most of the technologies defined for the non-service sectors. The technologies which are delayed include primarily advanced information processing and automation technologies, but also include some advanced manufacturing processes such as Rapson process papermaking, advanced electrolytic processes in chlorine and aluminum manufacture, steel mini-mills, and continuous casting of metals. By a coincidence of model formulation, the technology delays in the Delay All scenario also affect various energy conservation measures in the non-service sectors.

For both the Delay Services and Delay All cases, the delay pattern is as follows. Technologies which are available in the Baseline scenario in 1990 and 1995 are delayed by five years. Those available in 2000 and 2005 are delayed by ten years (commensurate, for instance, with their more speculative nature). Since the last period in the model is 2015, Baseline technologies for 2010 and 2015 are not available in the delay cases.

The third delay case addresses technologies which are not directly modeled as alternative production activities in PILOT. In formulating the alternative technologies, we have assumed that all future productivity growth in many sectors is captured by the alternative activities defined for increasing utilization of electronic equipment, that is, it occurs as a result of substituting electronics for labor. Sectors which are treated in this way include government, the service industries other than trade and communications, and the assembly-type manufacturing industries. Automation technologies are also defined for the other sectors, in addition to various energy conservation measures and important new manufacturing technologies. Nonetheless, the sheer diversity of new technologies in many sectors makes it quite impractical to define meaningful alternative aggregate production technologies. We have accordingly used sector-specific rates of labor productivity growth in some sectors as a proxy for new technologies that could not be explicitly modeled. To simulate the results of delays in these diverse technologies, we reduce the relevant sectoral productivity factors and thereby define a third delay case to be referred to as the Low Growth scenario. The basic intent is to lower the rate of productivity growth in the process industries by about the same amount as the reduction applied to the assembly-type manufacturing industries. This Low Growth case also subsumes the delays of the other two delay cases.

4.3 Key model assumptions conditioning the scenario results

In this section we discuss some key assumptions in the model which do not vary between the scenarios, but which determine the "environment" within which the equilibrium solutions are determined. These assumptions and corresponding model structures are kept the same across scenarios in order to isolate the effects attributable to the assumptions about technical change. The most important of these assumptions, in terms of how the current results are influenced, are probably those related to foreign trade. Other important assumptions are in such areas as consumer preferences, the actions of the government, and the financial structure of the model. Each of these is discussed below, focusing particularly on how the formulation is likely to have affected the results of the current study.

4.3.1 Foreign trade

Foreign trade is treated like another production activity in PILOT. Various commodities can be inputs or outputs, and there is a special intermediate commodity, "foreign currency", which is used or produced by the foreign trade activities. The most important feature of the treatment of foreign trade in PILOT is that net use of foreign currency over the horizon of the model, discounted at the interest rate used in the model, must be nonnegative. In other words, the U.S. must attain a net present value of its trade balance which is not in deficit. This does not prevent running a deficit at any particular point in time — indeed, the model often does so — but it does ensure that any deficit is eventually paid up sometime within the horizon of the model.

Foreign currency prices for imports are set exogenously at each point in time, but export prices are sensitive to the level of exports. This is a modification of the "small country" hypothesis which is common in the trade literature. Imports are treated as though the U.S. accounts for a small share of the market, but exports are not so treated. In order to increase U.S. exports of a particular commodity significantly above the current level, a decline in unit price must be suffered. This assumption is mainly motivated by a desire to prevent large bursts of exports in the model in response to small differences between domestic and foreign prices.

All four scenarios contain the same exogenously specified trends for prices of goods and services in the import/export markets. This reflects the scenario design assumption that the technology delays affect the U.S. and not the rest of the world. In the study reported here, foreign prices for many manufactured commodities, such as textiles, machinery, and motor vehicles, are set below U.S. prices in the early periods of the model, and are then reduced over time at a rate which is consistent with the rapid productivity growth that is expected to continue in Japan and in the newly industrialized countries of East Asia.

The most important effect of the assumptions on foreign trade just presented is to give

the model a great deal of flexibility in shifting net imports and exports over time, subject to some bounds imposed on the magnitudes of deficits or surpluses that can be accrued within any given period. This structure allows the model to run large trade deficits in early model periods provided that correspondingly large surpluses are achieved in the later periods, in order to balance the intertemporal accounts. It also gives the model flexibility at any particular point in time to shift trade among commodities in response to changes in comparative advantage arising from changes in technologies available. Thus, pessimistic assumptions on technology in only a few sectors are likely to have comparatively little effect on overall growth, but might easily induce very large effects on particular sectors as trade patterns follow changes in comparative advantage. These assumptions on foreign trade also serve to make aggregate output in the model particularly sensitive to changes in productivity in the service sectors, since these sectors not only employ a large fraction of the work force, they also cannot be traded, which means that inefficient domestic production cannot be replaced by imports.

In summary, then, the assumptions on foreign trade used in the study reported here have several implications. They focus our attention on technological changes that affect productivity in large sectors of the economy and particularly in sectors for which foreign trade is not a useful alternative. They also focus our attention on the ongoing effects of technological change in the long run, since near-term shortfalls in productivity growth can to a large degree be alleviated by net imports which are paid back in the future.

4.3.2 Consumer demand

Consumer preferences are a second important modeling assumption affecting the results of the study. The PILOT model as used in this study features price- and income-sensitive demand functions for eight aggregate commodities which happen to be primarily physical goods. On the other hand, it has fixed demands for five other commodities which include most consumer services. The fact that demands for most consumer services are fixed results from an analysis of past behavior. In the course of econometric estimation of consumer demand functions, we found that, in the historical data set, the demands for consumer services, such as health care and legal and professional services, were strongly *positively* correlated with their prices. As a consequence, any estimated model which fits the data well would not satisfy the integrability property required to obtain a computable model (this issue was discussed in Sections 2.1 and 2.5). The alternative of specifying fixed demands for consumer services makes the model particularly sensitive to changes in technology assumptions that affect the productivity of service sectors. This effect is then reinforced by the lack of trade in these sectors which was mentioned above.

The consumer demand functions used in this study also display a high income elasticity for consumption of housing and transportation. As an indication of this, in 1975 these commodities together absorbed about 57% of total expenditures on commodities which

are treated as income sensitive in PILOT. Compared to this average share, the estimated demand functions imply that, at 1972 benchmark prices, nearly two thirds of *incremental* expenditure would be allocated to these commodities. As a result, changes in technological assumptions which affect income have a strong effect on housing consumption, in particular, and in turn on the construction industry — even though the assumptions of the study include little technical change in the construction industry and little variation in technical change in construction across the scenarios.

Although consumer demand is an important factor in determining the results of the study, we expect that small changes in the parameters of the consumer demand functions would have relatively minor effects on the conclusions reached here. Since the statistical fits of these functions to historical data are quite good, uncertainty about the resulting parameters would appear to be unimportant as a source of uncertainty about the results of the study.

4.3.3 Government

The government is treated in a relatively stylized way in PILOT. Government expenditures are divided among commodities according to fixed proportions. One commodity is called "government services" and accounts for all of government labor (making the sector which produces it the largest of any sector in terms of labor use). The government services sector is subject to labor saving due to automation as is any other.

It is possible to have flat-rate taxes on physical flows of consumption and investment and on output rates in the various production sectors. In the scenarios reported here, no taxes are placed on investment because doing so in preliminary runs seemed to induce difficulties in convergence of the solution process. Marginal tax rates on consumption are specified to be relatively high in the early periods and to decline somewhat through the 1980s, with a lump-sum rebate used to allow adjusting the actual level of government expenditures independent of the tax rate. Accordingly, having flat-rate consumption taxes and no investment tax in the model reduces distortions attributable to the tax system to almost nil. It would be desirable to test the implications of such distortions by incorporating some representation of the actual tax system, but the associated computational difficulties made that impractical in the current study.

4.3.4 Other important assumptions

Another potentially important input assumption is the general trend in world oil prices. In the present study, the assumed trend follows the median results from the July 1987 poll of the International Energy Workshop. Prices fall about 20 percent between 1985 and 1990 and then grow fairly steadily at just over 4 percent per year thereafter. The presence in PILOT of upward-sloping imported oil supply curves in each period causes the attained

price to vary between scenarios in accordance with demand pressure, but these variations are not significant across the four scenarios studied.

Several additional points about the model undoubtedly have some influence on the results reported here, but it is impossible at this time to analyze the nature of the effects produced. As discussed in Section 1, agents have perfect foresight in the model as currently formulated. This lack of uncertainty in agents' calculations and the resulting lack of an interesting financial system is clearly one feature of the model the effects of which we cannot analyze. A second is the *ad hoc* approach taken to computing valuations for capital stocks carried over to the post-horizon period, a factor which conditions the profitability of investments in the later model periods. A third is a simplifying assumption necessitated by computational considerations: newly built production capacity in the model is assumed to depreciate according to a fixed schedule and, in particular, cannot be retired early for economic reasons.

5

SCENARIO RESULTS

The technology specifications and availability patterns characterizing the Baseline and delayed technology scenarios give rise to four distinct general equilibrium solutions of the PILOT model. By comparing economic measures across these solutions, we may begin to draw some meaningful conclusions about the basic economic effects of the kinds of technological change that is modeled. In this section, we present the salient results of this scenario analysis and attempt to analyze the underlying economic and technological forces which account for the observed differences in economic performance across the four scenarios.

The most important result which emerges from this analysis is that delaying the availability of new technologies significantly reduces overall economic performance, which is not unexpected. The raw facts behind this conclusion are presented in the first subsection below, and some of its policy implications are discussed in Section 5.4. Our analysis also results in some conclusions that are unexpected, particularly when it is focussed at the level of individual sectors, in Section 5.2. Some sectors are found to be quite sensitive to changes in total income. Construction is one such sector. The indirect effects on the construction industry of delaying availability of new technologies in other sectors, mediated by changes in income, are large — even though the direct effects are small. Some sectors are strongly affected by changes in patterns of imports and exports which result from technology delays in other sectors. The chemicals and primary metals industries, for example, have higher output in some of the delay cases than they do in the Baseline, because imports of them are reduced so that other commodities can be imported instead. Some of the effects on energy consumption of the technology delays we have studied (discussed in Section 5.3 below) are also quite unexpected. Energy consumption is found to be much more sensitive to changes in the output of certain industries than it is to changes in overall economic performance, and the industries which affect energy consumption most are some of those for which output is least highly correlated with GNP. These results of our analysis provide ample demonstration of the proposition that a general equilibrium model is essential for studying the economic effects of technical change.

The Appendix to this report contains a number of figures presenting various measures of economic performance and energy utilization for the four scenarios. The first eleven figures pertain to Gross National Product (GNP) and its components. The next group of figures reports net export shares and output levels for six selected industries that are significantly influenced by the changes in technology availability. The third set of figures presents the derived effects on total primary energy and oil products consumption and on electricity consumption by sector. The final two figures address the energy intensity of GNP and the share of electricity in total energy consumption.

5.1 Macroeconomic aggregates

The effects of the delays in technological innovation are just noticeable in 1990 and become more pronounced thereafter. Over the 1985-2010 horizon, GNP grows at an average annual rate of 2.9 percent in the Baseline. This growth rate drops monotonically through the delay cases to a low of 2.2 percent in the Low Growth scenario, as shown in Figure 1. In partial contrast, Figure 2 shows that the effects on personal consumption expenditures are somewhat erratic, though small in magnitude, through 1995. This is attributable primarily to the perfect foresight feature of the model, since foregoing consumption for investment is seen to pay off less in terms of increased future consumption possibilities in the delay cases. Over 25 years the average annual rate of growth in consumption falls from 2.7 percent to 2.0 percent between the Baseline and Low Growth scenarios. These differences in growth rates of GNP and consumption compound to a divergence across scenarios of 13-16 percent by 2010. The average annual rate of growth in *per capita* consumption expenditures in the Baseline scenario is about 2 percent, which is the growth rate that has actually prevailed in the U.S. — with remarkably little variation — since the late 1940's.

Investment expenditures, displayed in Figure 3, show more variation across scenarios than do consumption and GNP as a whole. (Note that 1985 is a "projection" year in PILOT and that investment levels differ more noticeably across scenarios in 1985 than do the other components of GNP.) The average annual rate of growth in investment declines from 2.8 percent in the Baseline to 2.0-2.2 percent in the delay cases. The compounded effect by 2010 is a 19 percent drop between Baseline and Delay Services and a 27 percent drop between Baseline and Low Growth. In order to understand the behavior of total investment expenditures, it is necessary to examine the individual components of investment, as is done in Section 5.1.2 below.

The results for other components of GNP are less interesting. Government expenditures are calibrated in PILOT to be approximately 30 percent of consumption expenditures. The intertemporal balance of payments constraint, coupled with upper bounds on the magnitude of any deficit or surplus in a given period, results in an aggregate net exports pattern that is virtually the same in all scenarios: significant net imports in 1985-1995 followed by growing net exports thereafter, as seen in Figure 4.

The delays in technological innovation do not affect the various components of consumption and investment expenditures in the same way, and differences in these effects are important in explaining the induced effects on energy consumption reported in Section 5.3.

5.1.1 Components of consumption

In the present study, the most important variations in consumption expenditures occur in the categories of housing and transportation, the results for which are depicted in Figures

5 and 6. For completeness, Figure 7 presents aggregate expenditures on the other six commodities for which consumption in the model is a function of relative prices and income allocated to consumption. (Consumption of five additional commodities is specified exogenously in the model and does not vary across scenarios. Section 3.5 provides a list of all consumption categories.)

Housing is the largest component of consumption expenditures and is the one most significantly affected by the technology delays, both in absolute and proportional terms. By 2010 housing expenditure is some 28 percent less in the Low Growth scenario than in the Baseline. As the share of housing in total variable consumption expenditures also declines across scenarios, it is reasonable to conclude that both price effects and income effects are at work.

Expenditure on transportation is the second largest individual component, and it is somewhat more significantly affected, on a proportional basis, than the aggregate of the other six variable consumption commodities. Transportation expenditure in 2010 is down some 16 percent in the Low Growth case relative to Baseline. The transportation share of expenditures increases slightly across scenarios, indicating that the predominate source of the decline in expenditure is the income effect.

5.1.2 *Components of investment*

Investment expenditure on buildings is driven both by housing consumption and industrial output levels, which induce a demand for both industrial and commercial buildings. As can be seen in Figure 8, buildings investment is very significantly affected by the delays in technological innovation, especially those captured in the Delay Services and Low Growth scenarios. By 2010, buildings investment decreases by 22 percent between the Baseline and Delay Services scenarios and by 42 percent between Baseline and Low Growth.

On a proportional basis, the level of investment expenditure on computers is even more significantly reduced, as would be expected from the nature of the technology delays modeled. This is shown in Figure 9. From 1990 onward, the delays in service sector computer utilization represented in the Delay Services case reduce computer investment by 20-30 percent relative to the Baseline. Computer investment levels are quite similar in the Delay All and Low Growth scenarios, with reductions relative to Baseline of 42 percent in 1990, over 50 percent in 1995-2005, and about 33 percent in 2010.

Communications equipment is another investment commodity whose demand is greatly reduced by the technology delays. Figure 10 clearly indicates that almost all of the decrease is attributable to the delay in service sector technologies. Considering the delay cases as a group, the reductions in communications equipment investment are on the order of 10 percent in 1990, widening to 35 percent in 2000, and "rebounding" to 15 percent in 2010.

For the most part, these investment levels track the output levels of the business services sector.

Expenditures on twelve other investment commodities are presented as an aggregate in Figure 11. The departures from a pattern of declining levels across the four scenarios indicate that such investment expenditures are more sensitive to the composition of industrial output than to the overall level of economic growth.

5.1.3 Analysis of macroeconomic effects

There seem to be three predominant economic factors that affect aggregate economic performance in the model. The first is the relatively high sensitivity of residential housing consumption to changes in income. The second is a combined effect of the size of the service sector, the fixed consumption profiles for a number of service-related consumption items, and the limited opportunities for foreign trade in services. The third is the sensitivity of patterns of international trade to changes in comparative advantage. This last factor will be discussed in the next subsection.

The effect of changes in incremental income on the demand for residential housing in the U.S. is quite strong, at least according to the consumer demand functions estimated for PILOT. As an indication, total consumer expenditure in 2010 is reduced by 5.5 percent between the Baseline and Delay Services scenarios, while expenditure on housing is reduced by 11.9 percent. Compounding this effect is the logical consequence that a given change in the demand for housing translates into a proportionally much larger change in the rate of new investment in the housing stock. Since investment in buildings is a large component of overall investment expenditure, the net effect of the income reduction from delaying service technologies is a marked reduction in both consumption and investment.

The significant reductions in total and buildings investment, particularly in the Delay Services case, are at odds with the (erroneous) conclusions that might be derived from two independent *ceteris paribus* analyses. Since the service sectors are on the whole less capital-intensive than the manufacturing industries, a simple analysis would suggest that lowering the rate of technical change in services would not have a marked effect on total investment. The general equilibrium analysis, however, shows the indirect effects through consumer income to be quite pronounced. Another simple analysis is focused on the construction industry and the observation that automation has almost no effect on productivity in this sector. In fact, construction productivity in PILOT is essentially the same in all periods in all scenarios.¹ A naive expectation would be that the construction industry should, if anything, do somewhat better than the economy as a whole when productivity growth is reduced in other sectors. Again, the indirect effects through income prove to be more

¹There has been no measured improvement in construction productivity in over twenty years, indeed by some measures it has declined over the last twenty years.

important than the direct effects on relative costs of production.

In many respects, the macroeconomic effects of delaying service sector technologies are more pronounced than the additional effects of delaying technologies in manufacturing sectors. There are three principal reasons for this disproportionate influence. First, the service sectors employ the vast majority of workers in the U.S. economy. In the Baseline scenario, for instance, about 67 percent of the workforce is in the service sectors, and this value is nearly constant throughout the horizon of the model. The importance of the sheer size of the service sectors outweighs the fact that manufacturing, because it achieves larger productivity improvements due to automation, has more to lose if automation is delayed. The second reason is the specification in PILOT of fixed *per capita* demand levels for five aggregate commodities which include important services such as health care and personal business services. These fixed levels do not then allow for a reduction in demand in response to either higher prices for the services or lower consumer income. As a result, the output levels for key service sectors cannot change markedly across scenarios, even in the face of reduced service sector productivity. Domestic output levels are maintained because of the third reason for a disproportionate influence of service sectors, the fact that the demand for services cannot be supplied from foreign sources because the opportunities for international trade in services are very limited, both in the model and in reality.

5.2 Net exports and output levels for selected industries

In sharp contrast to the situation with services, dramatic swings in international trade patterns are a predominant factor in tracing the economic reactions to delaying technology in the manufacturing sectors. Figures 12-17 present the patterns of net exports and output levels for six industries that are strongly affected by the technology delays represented in the Delay All and Low Growth scenarios. Three of these are basic process industries (chemicals, steel, and nonferrous metals) for which the responses are in some sense mirror images of the other three industries, which are all assembly-type manufacturing (heavy machinery, industrial machinery, and motor vehicles).

The tabulated values for net export shares are calculated as follows. If net exports are positive, then the indicated share is the ratio of net exports to total production. It thus represents how much of domestic production is dedicated to sales abroad. If net exports are negative (i.e., the U.S. is a net importer), then the indicated share is the ratio of net exports to total domestic consumption of the commodity. It then represents how much of domestic consumption is supplied by foreign sources. The associated swings in sector output levels will prove to be important in explaining the induced effects on energy consumption reported in the next subsection.

The patterns for each industry in exports and output levels naturally reflect particular idiosyncrasies in the timing of new domestic technology relative to trends for world market

prices. Some of these are quite surprising — for instance, the dramatic resurgence of the nonferrous metals industry in the Baseline solution for 2000. Idiosyncrasies notwithstanding, two important general observations can be made. The first is that there is a pattern of significant and increasing import dependence for all six industries in all scenarios through at least 1995. This phenomenon reflects the perfect foresight feature of the model, as imports are used heavily in early periods in anticipation of counterbalancing exports in later periods, when more advanced production technology becomes available.

The second observation is that the process industries and the assembly industries display almost exactly opposite patterns of import and output movements in 2000 and beyond. This reflects the effects of the technology delays on comparative advantage. In the Baseline and Delay Services scenarios, the assumed patterns of technological advance in manufacturing imply greater rates of productivity increase in the assembly industries than in the process industries. It is then natural to substitute imports for the outputs of the process industries and use exports of assembled manufactured goods to balance not only current imports but also the accumulated deficits from earlier periods. In the Delay All case, the rate of productivity increase in the assembly industries is significantly reduced. This largely reverses the incentives just described, and leads to significant imports of assembled goods balanced by exports of basic commodities. It is interesting that the further reductions in productivity growth in the Low Growth case — which pertain primarily to the process industries — do little to affect the import/export patterns of the Delay All case.

5.3 *Derived effects on energy consumption*

Figure 18 depicts total primary energy consumption for each of the four scenarios. In making up this total, the contribution from natural gas, nuclear, and alternative sources is the same across all scenarios. This is because PILOT almost always utilizes these preferred energy sources at their exogenously specified upper bounds. Accordingly, the large variations in total energy use are all allocated to coal and oil products. Swings in coal consumption of 10-20 percent across scenarios are in large part related to its use for electricity generation, which will be discussed presently. There is also in 2000-2010 a significantly greater use of coal for feedstock and industrial heat and power in the Delay All and Low Growth scenarios, relative to the Baseline and Delay Services cases. This use is directly related to higher output levels for the chemicals and metals industries.

Even wider swings are apparent in Figure 19 for oil products consumption. Consumption of oil by utilities and in residential and commercial buildings is virtually the same across scenarios. Consumption for non-automobile transportation generally tracks overall economic growth. Gasoline use in personal automobiles follows the pattern of transportation consumption shown in Figure 6, as oil prices which are similar in all scenarios lead to vehicle efficiency profiles which also change very little. Together, transportation uses of oil products

in 1995-2010 fall about 1-2 quad from each scenario to the next. Overriding this monotonic decline is significantly greater use of oil for feedstock and industrial heat and power in the Delay All and Low Growth scenarios. This is the same pattern as for coal use and follows output levels in chemicals and metals. There is also an important multiplier effect through the use of oil for producing indirect heat in petroleum refining.

A sectoral breakdown is similarly important in explaining the patterns in electricity consumption. Electricity use in the residential and commercial sectors (see Figures 20 and 21) declines monotonically across the scenarios, driven by the underlying demands for housing and commercial building space. These declines are offset, however, by the larger (absolute) swings in industrial electricity consumption presented in Figure 22. In PILOT, industrial electricity use is divided into two categories: motor and miscellaneous uses, and larger scale heating, electrolytic, and other process uses. Motor and miscellaneous uses increase over time in all scenarios from about 0.6 TKWH in 1985 to 1.1-1.2 TKWH in 2010. Differences in the inter-period growth pattern across scenarios account for about half of the swings in overall industrial use of electricity. Process-oriented electricity use, however, closely follows output levels in the electricity-intensive chemicals and metals industries. Thus, the distinctive pattern of industrial electricity use in 2000 and beyond reflects the patterns observed in Figures 12-14 for the output levels of these process industries, particularly that for non-ferrous metals. When the figures for industrial consumption are added to those for the residential and commercial sectors, the overall electricity consumption levels are somewhat more stable across scenarios (see Figure 23), but the influence of process electricity use is still visible.

5.3.1 Energy and electricity intensity of GNP

It is apparent from examining Figure 24 that total energy consumption does not follow a simple proportional relationship to GNP, but it depends, rather, on the composition of GNP and industrial output. Total energy use per unit of GNP is virtually the same in the Baseline and Delay Services cases and demonstrates a pronounced downward trend through 2010. This trend reflects both an increased efficiency in the use of energy and a decline in the relative importance of energy-intensive industries. The energy/GNP ratio is also very similar in the Delay All and Low Growth scenarios, but stays higher than the ratio for the other two cases between 1985 and 2010. This is partially attributable to delays in energy conservation technologies, but is primarily related to higher output levels for energy-intensive manufacturing (as seen in Figures 12-14). Moreover, energy use per unit of GNP in the Delay All and Low Growth scenarios actually increases between 2000 and 2005, with the result that total energy use in 2005 is comparable to or even higher than that observed in the Baseline.

The share of electricity in total energy consumption is depicted in Figure 25.² All four scenarios display a continuing upward trend, with very little difference between scenarios through 2000. The divergence after 2000 represents the net effect of a complicated array of movements in residential/commercial energy consumption and in output levels (with associated oil and electricity use) in the chemicals and metals industries.

5.4 Policy implications

We have found that the economic costs of delaying new technology can be large, implying that public policies should be carefully examined to assess their interaction with the development and domestic utilization of new production technology. Government funding of research and development, R & D tax credits, investment tax credits, and patent and copyright laws are all public policies which have important and direct effects on the adoption of advanced technologies. In addition, foreign trade policy may have significant indirect effects. Our results show that dramatic changes in import/export patterns are an important mechanism for mediating the effects of changes in technological innovation, which points to the existence of important relationships between technological change and patterns of trade that are not limited to the one-way causal link addressed in this study.

In addition, there are other areas in which policy choices might be made that would have large effects on technical change, and on the availability of automation technologies in particular. There are reasons to believe that there are significant market imperfections which would act to discourage adoption of these technologies, and if there are, alleviating them could be a very valuable policy intervention. Adoption of automation could be influenced by two types of market imperfections. Neither of them can be directly represented in the PILOT model, but they could certainly be adduced as the reasons for the technology delays which we have studied in this paper.

Electronics-based automation technologies are subject to the usual network externalities. The most efficient ways to use computers for many tasks involve communication between separate computers. Purchase orders, design data, and many other sorts of information can be exchanged faster and more accurately if they go directly from computer to computer. As a result, the benefits to each individual user of using computer-based automation technologies are in part dependent on the number of other users who have compatible equipment. An individual user in his own cost/benefit calculations, however, does not necessarily consider the benefits derived by *others* from the opportunity to connect with *him*, and so he may

²The discrepancy between PILOT results for 1985 and history interestingly does not result primarily from lower electricity use in the model. Model GNP and total energy use are higher than actual in 1985, but the energy/GNP ratio is very close to the actual, as can be seen in Figure 24. The "excess" energy consumption is largely localized to use of natural gas in the residential and commercial sectors. Since total electricity use in the model is close to actual, the visible result in Figure 25 is an electricity share that is lower than actual.

not be led to make investments in computer-based automation which are actually desirable from the point of view of society as a whole.

It seems that there is little that can be done about the conventional network externality problem discussed in the last paragraph. There is a related problem, however, which may be amenable to some sort of intervention. The term "compatible equipment" in the discussion above is quite important. It is quite possible that having universal standards for exchanging various types of information (sending letters, placing orders with suppliers, and so forth) in electronic format would significantly enhance the rate at which automation technologies are adopted. If it does, then as we have seen, the benefits to society as a whole could be enormous. Enabling the U.S. to realize the Baseline scenario instead of one of the delay scenarios would be worth tens of billions of dollars in net present value of consumption benefits, accumulated over the next 25 years. It would be well worth investigating whether intervention by the government or some other standard-setting organization is needed in order to secure these benefits.

5.5 Conclusions about methodology

We believe that the methodological development and scenario analysis presented in this paper effectively demonstrate the feasibility and desirability of a computable general equilibrium approach to analyzing the economy-wide effects of a phenomenon such as technological change. By focussing on aggregate producer and consumer behavior, it is possible to make acceptable restrictions on the functional forms used to represent production and consumption that allow for the computation of an equilibrium solution by means of techniques based on mathematical programming. Because it is currently feasible to solve linearly constrained mathematical programs containing thousands of variables and relations, it becomes possible to construct and solve an equilibrium model of such dimensions. The PILOT model is a sophisticated example of a large-scale computable general equilibrium model which is uniquely well suited to the study of technical changes in the production sector of the economy. The scenario analysis presented in this section nicely illustrates the analytical advantages of the general equilibrium perspective. By far the most interesting effects of changing patterns of availability for advanced technology turn out to be *indirect* effects mediated through shifts in comparative advantage in international trade and through income effects in personal consumption. The only rigorous way to capture such effects is through the use of a general equilibrium analysis.

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APPENDIX

Figures 1 through 25

FIGURE 1
GROSS NATIONAL PRODUCT

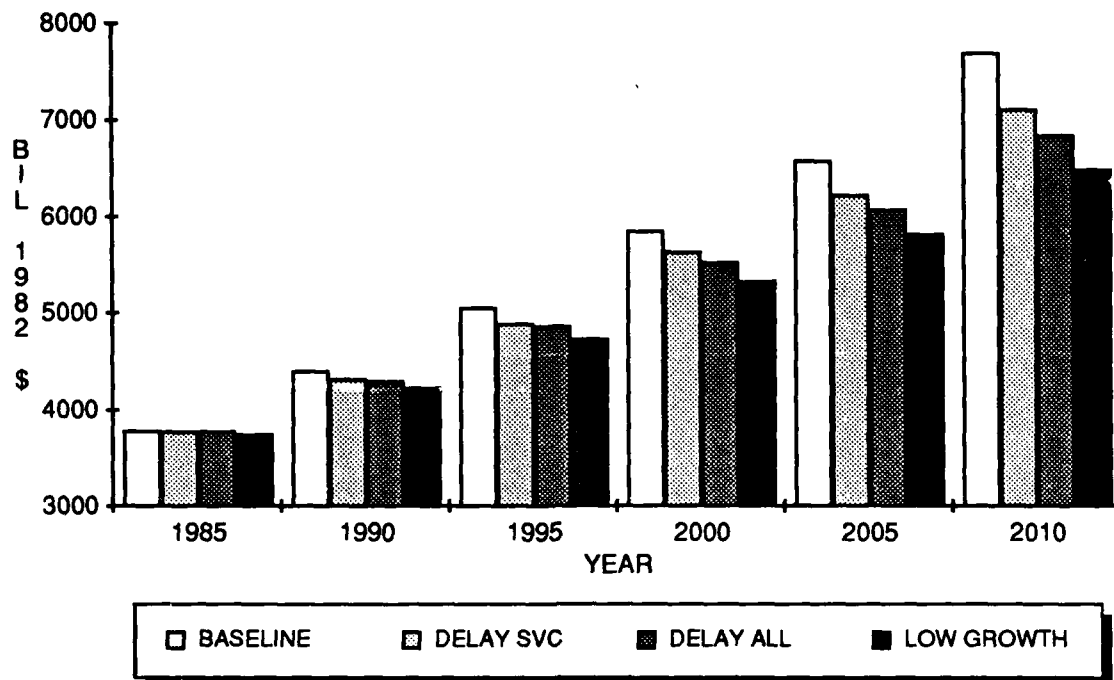


FIGURE 2
PERSONAL CONSUMPTION

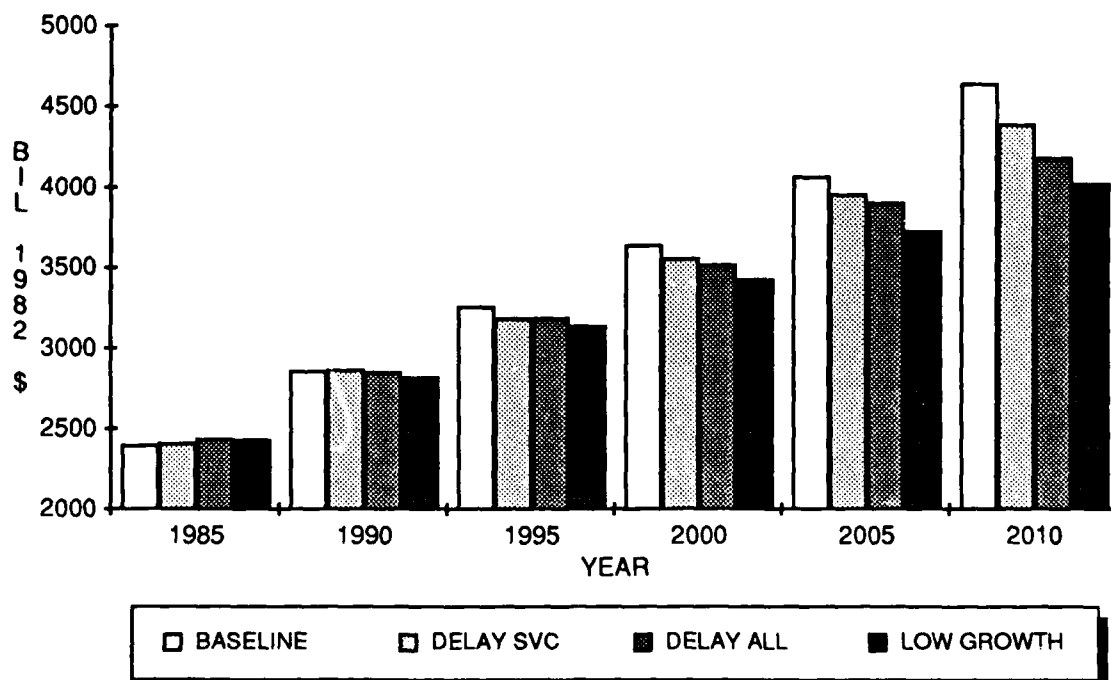


FIGURE 3
INVESTMENT

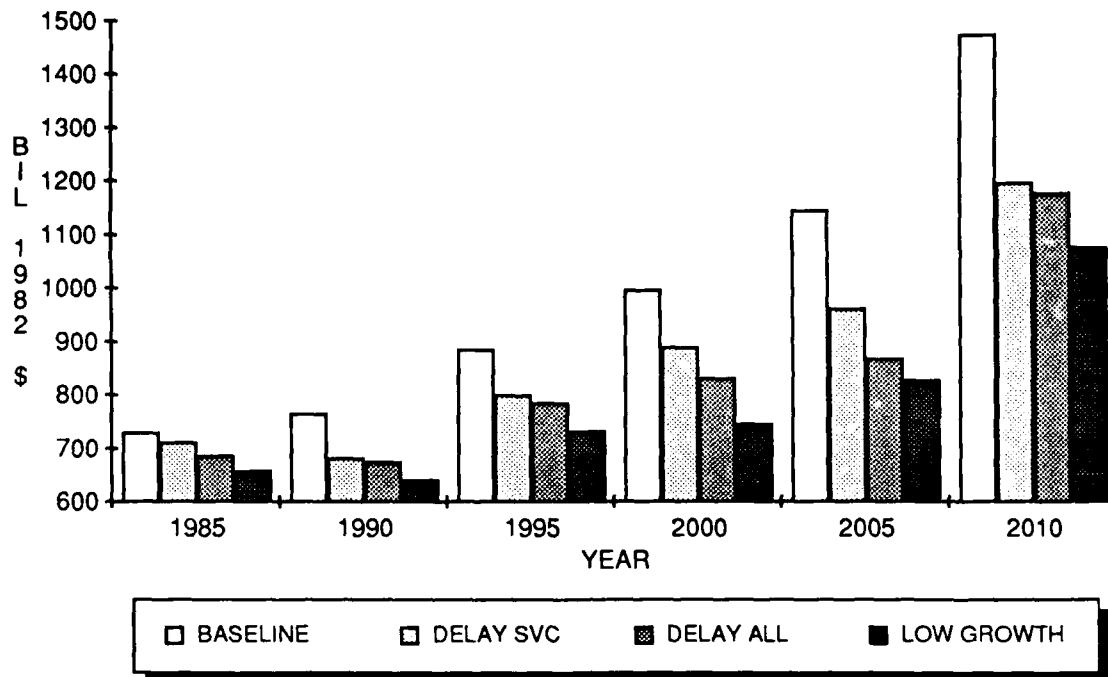


FIGURE 4
NET EXPORTS

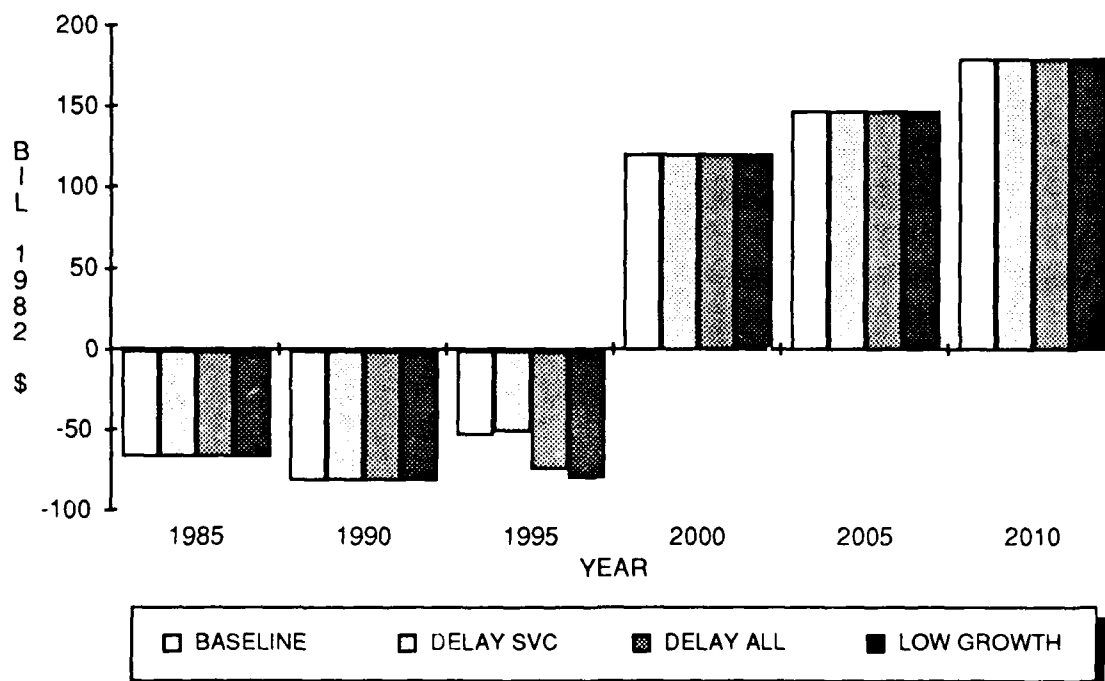


FIGURE 5
CONSUMPTION EXPENDITURE
HOUSING

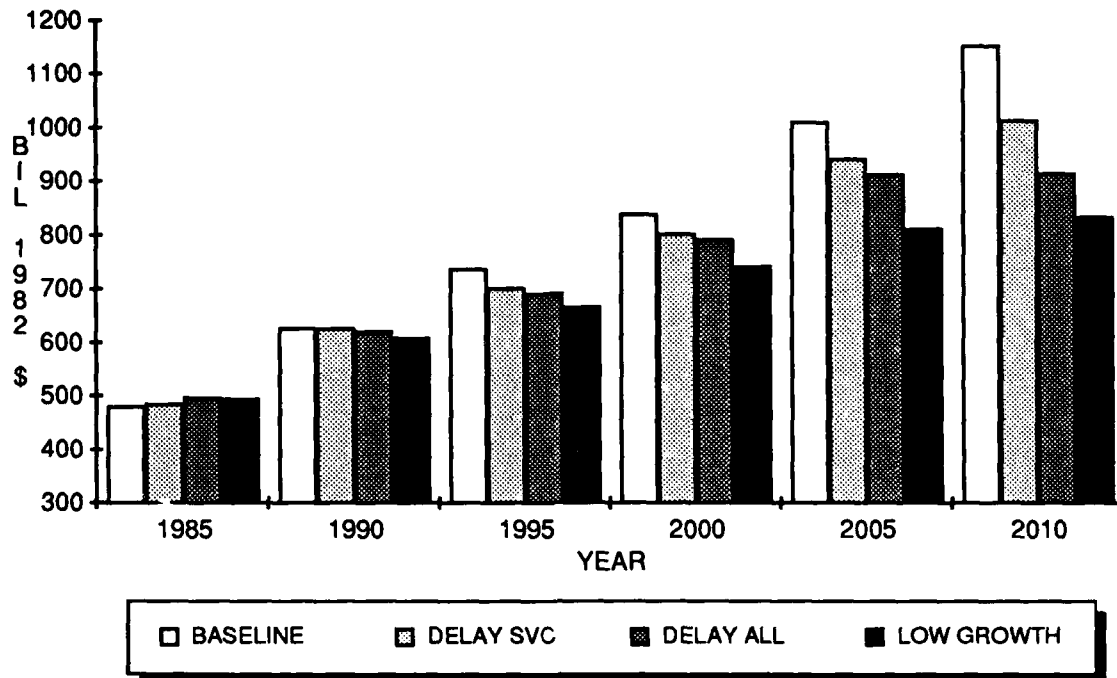


FIGURE 6
CONSUMPTION EXPENDITURE
TRANSPORTATION

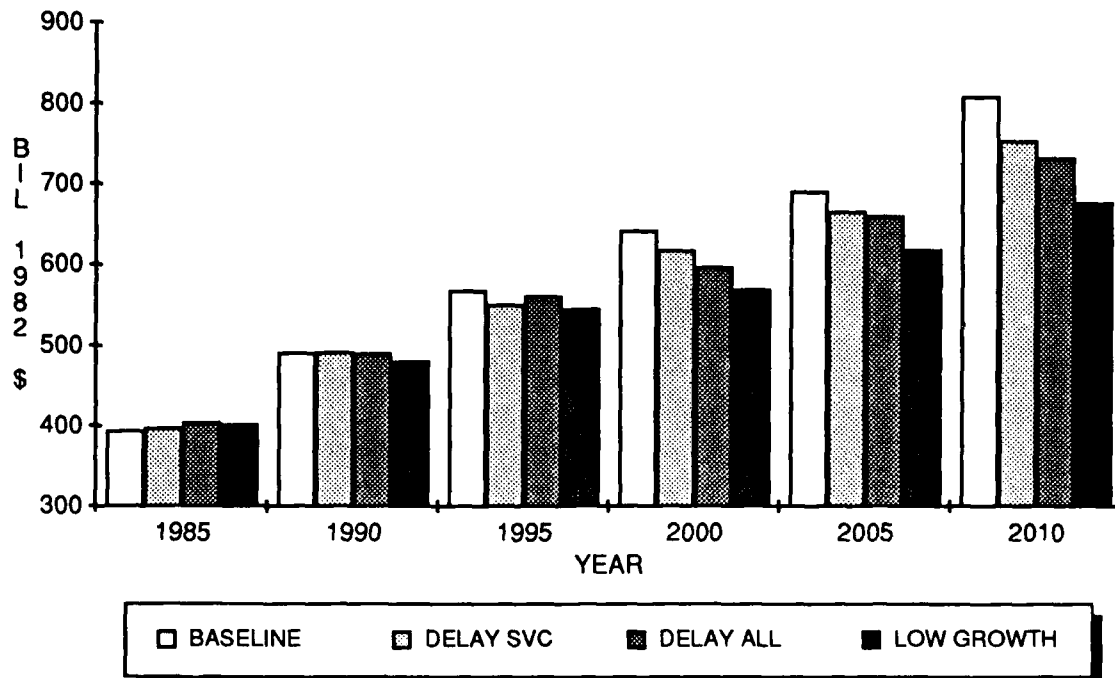


FIGURE 7
CONSUMPTION EXPENDITURE
OTHER VARIABLE

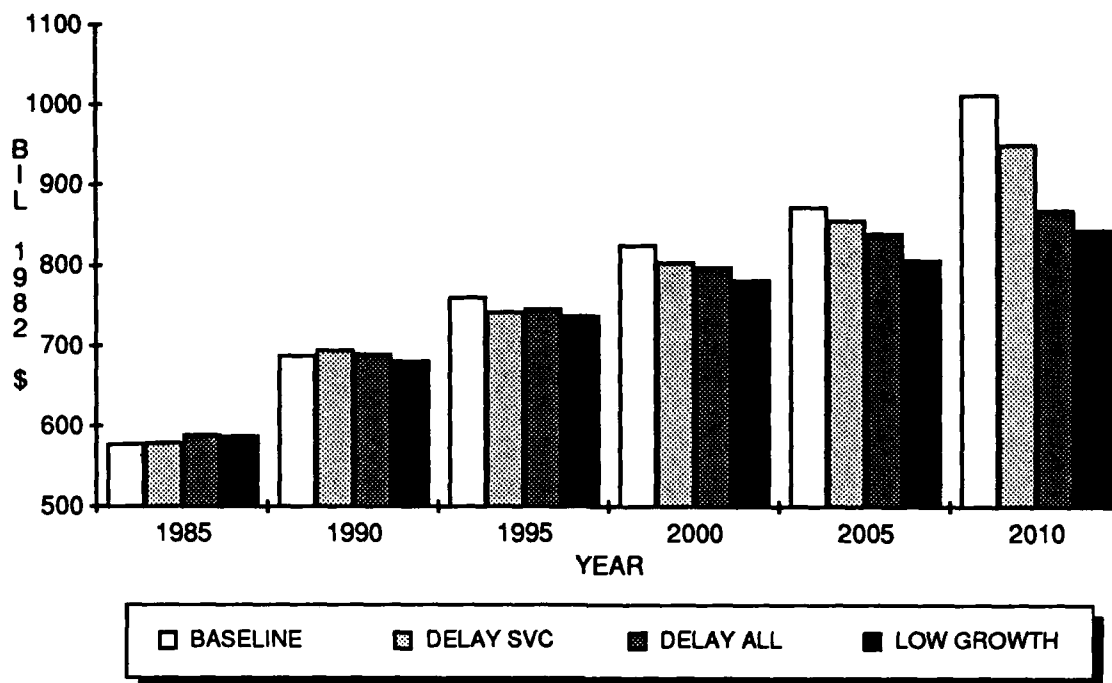


FIGURE 8
INVESTMENT EXPENDITURE
BUILDINGS

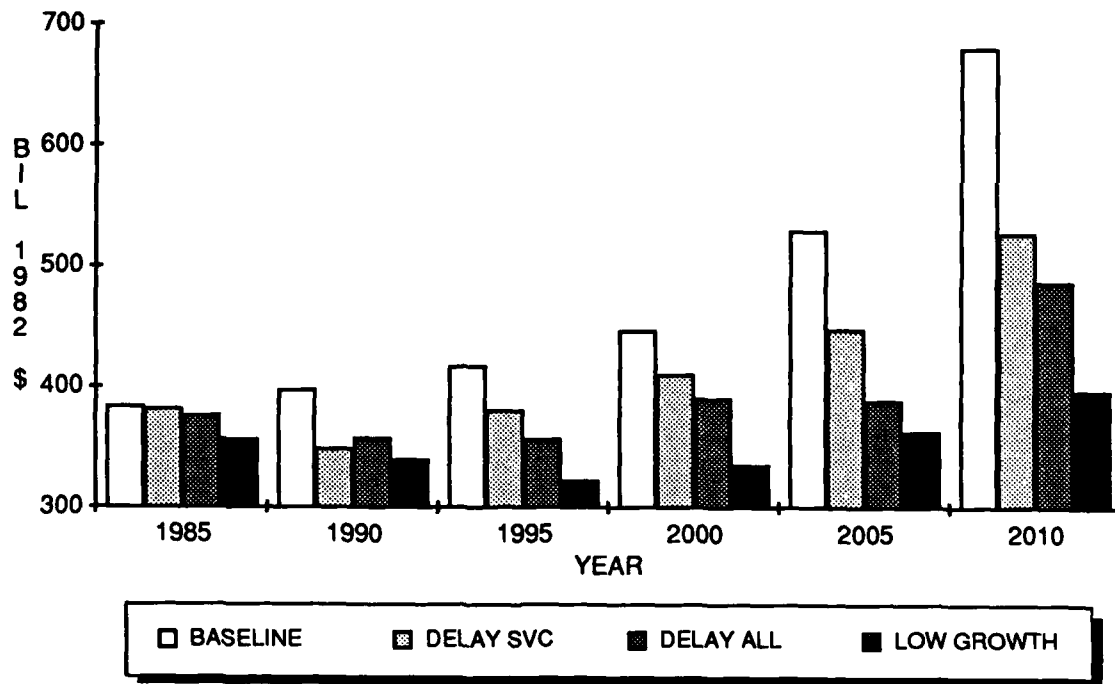


FIGURE 9
INVESTMENT EXPENDITURE
COMPUTERS

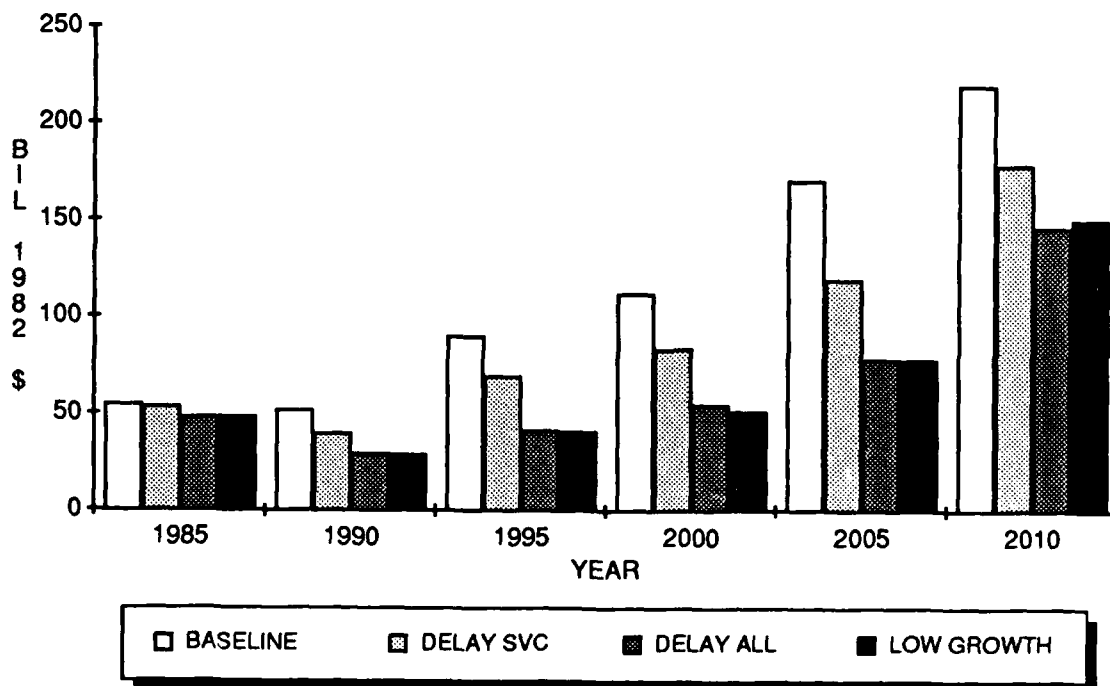


FIGURE 10
INVESTMENT EXPENDITURE
COMMUNICATIONS EQUIPMENT

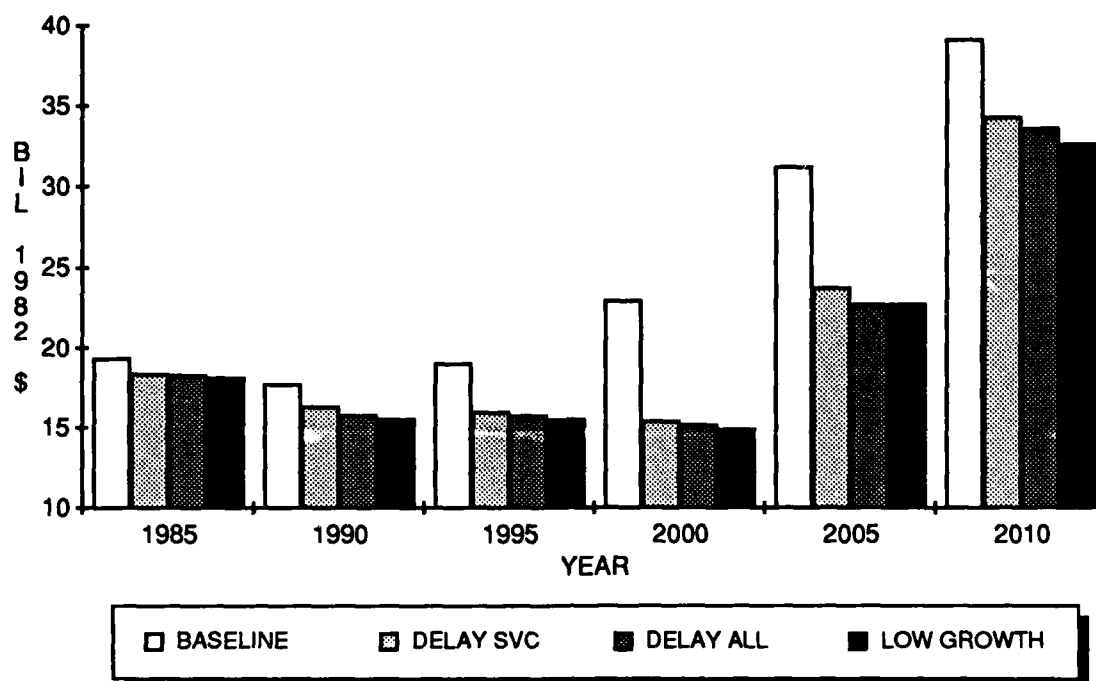


FIGURE 11
INVESTMENT EXPENDITURE
OTHER EQUIPMENT

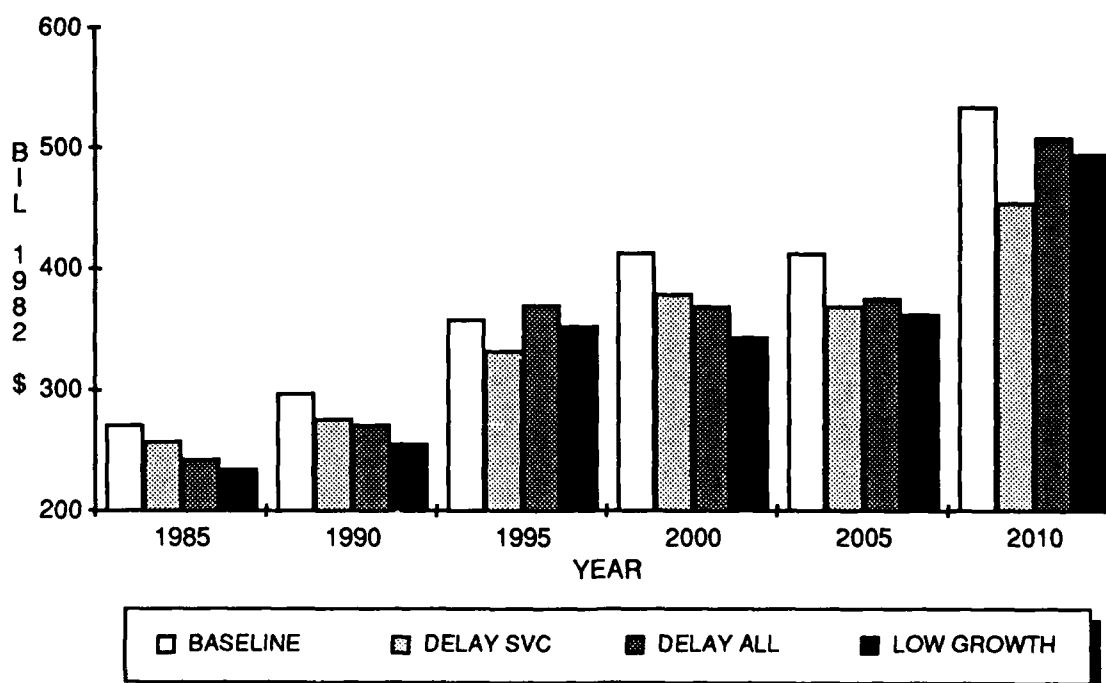


FIGURE 12a
NET EXPORT SHARES - CHEMICALS

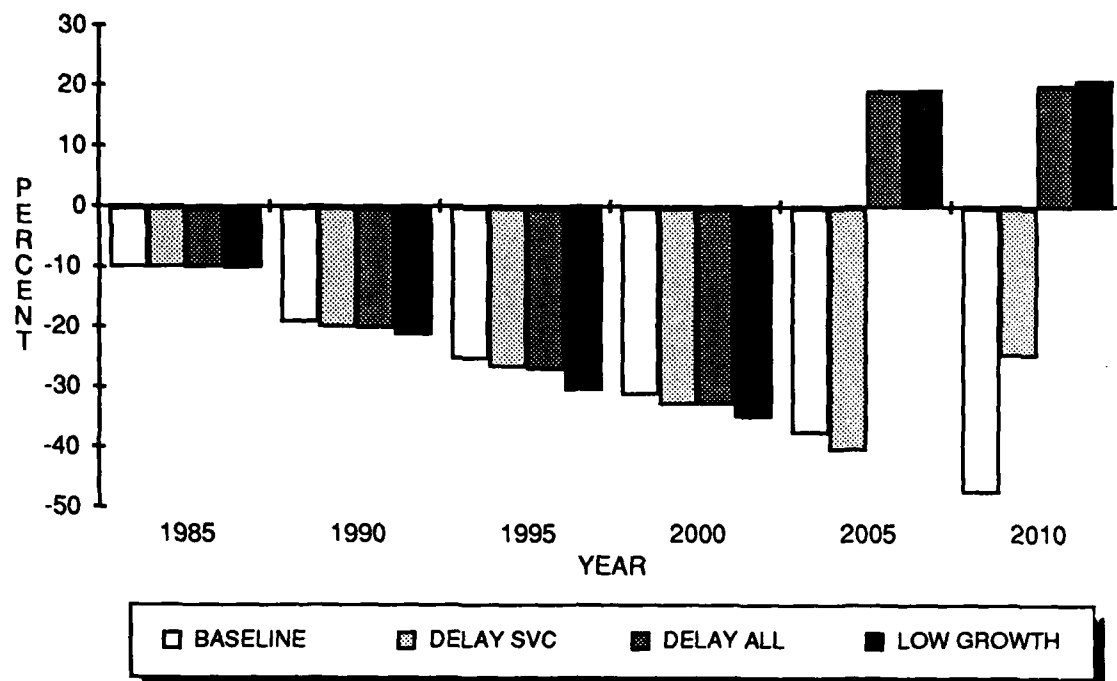


FIGURE 12b
OUTPUT LEVELS - CHEMICALS

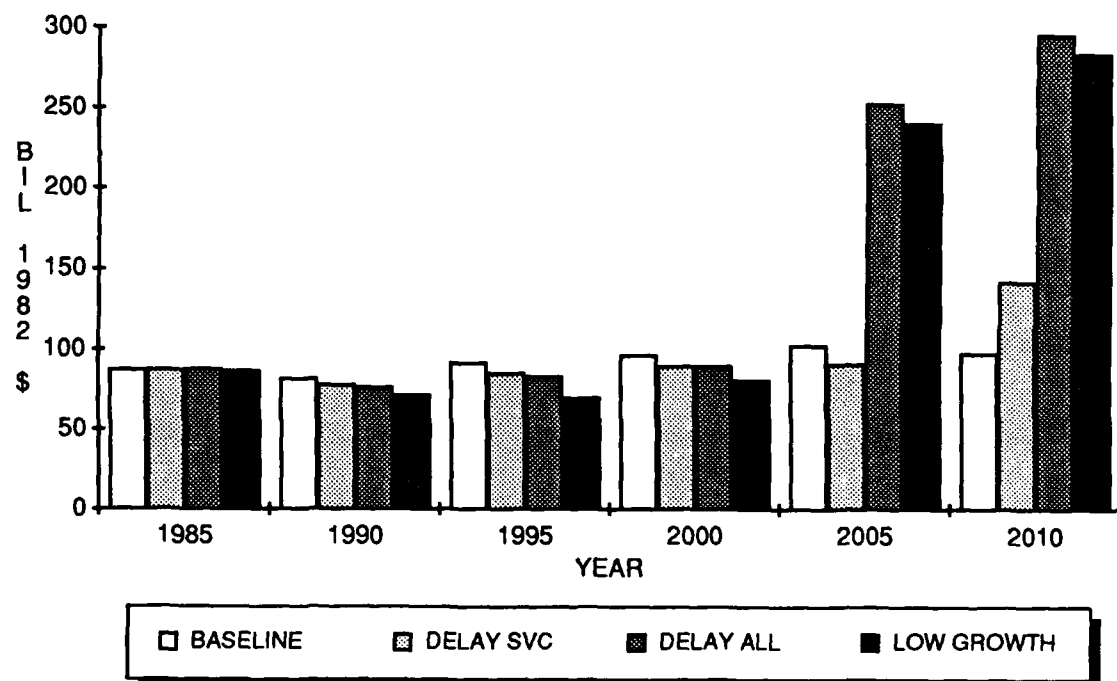


FIGURE 13a
NET EXPORT SHARES - STEEL

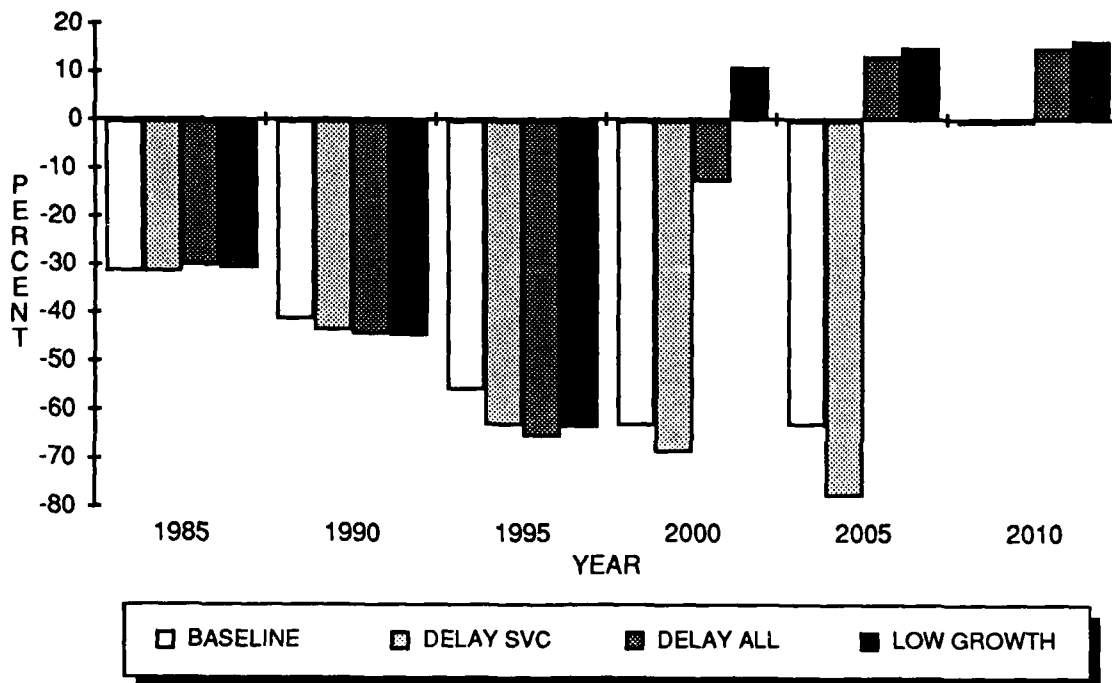


FIGURE 13b
OUTPUT LEVELS - STEEL

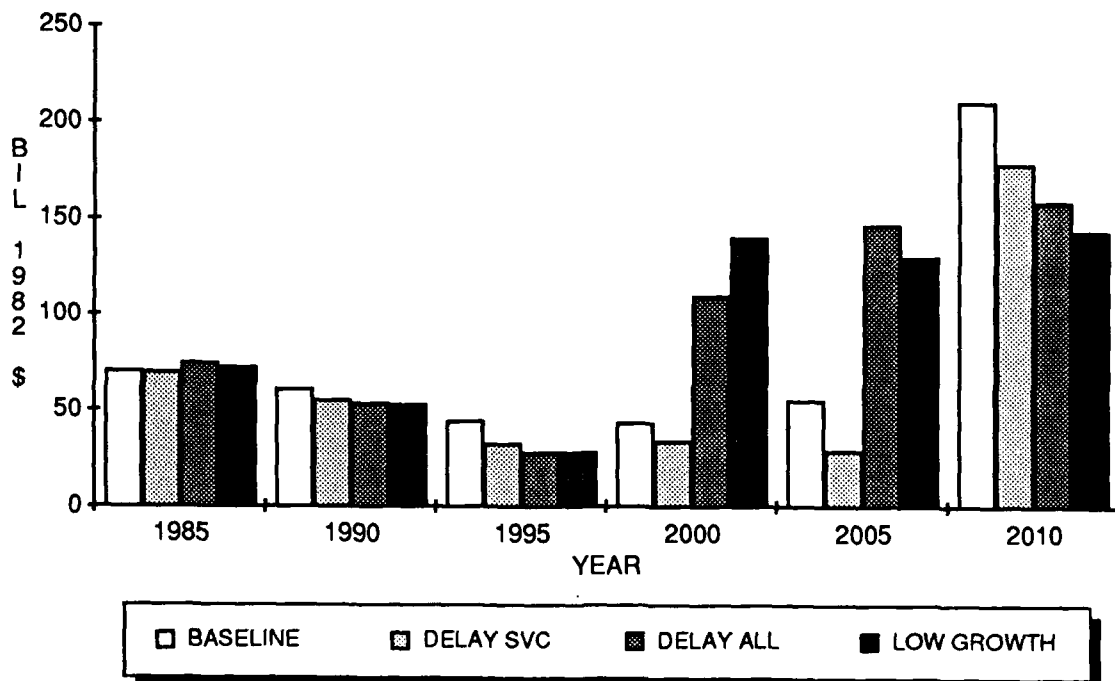


FIGURE 14a
NET EXPORT SHARES - NONFERROUS METALS

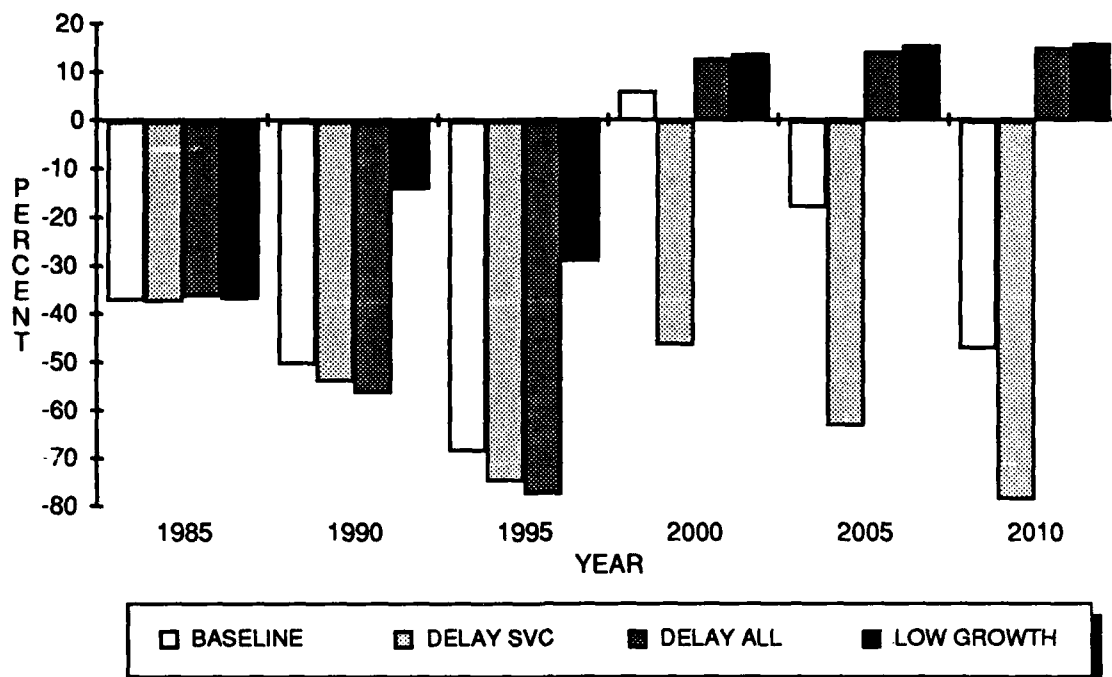


FIGURE 14b
OUTPUT LEVELS - NONFERROUS METALS

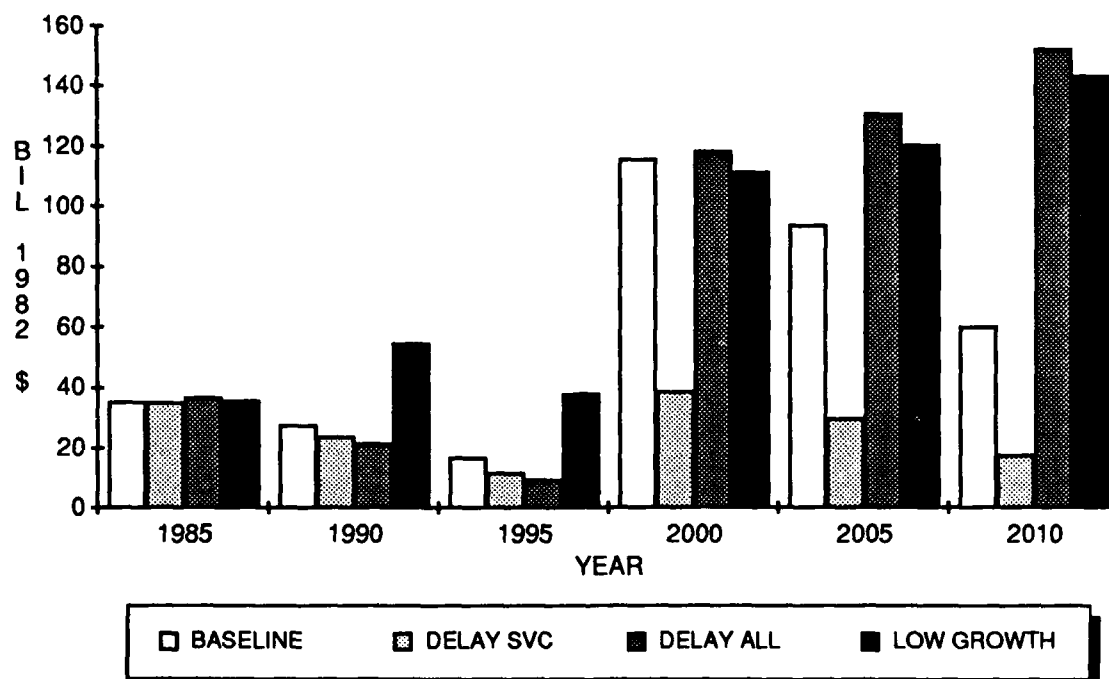


FIGURE 15a
NET EXPORT SHARES - HEAVY MACHINERY

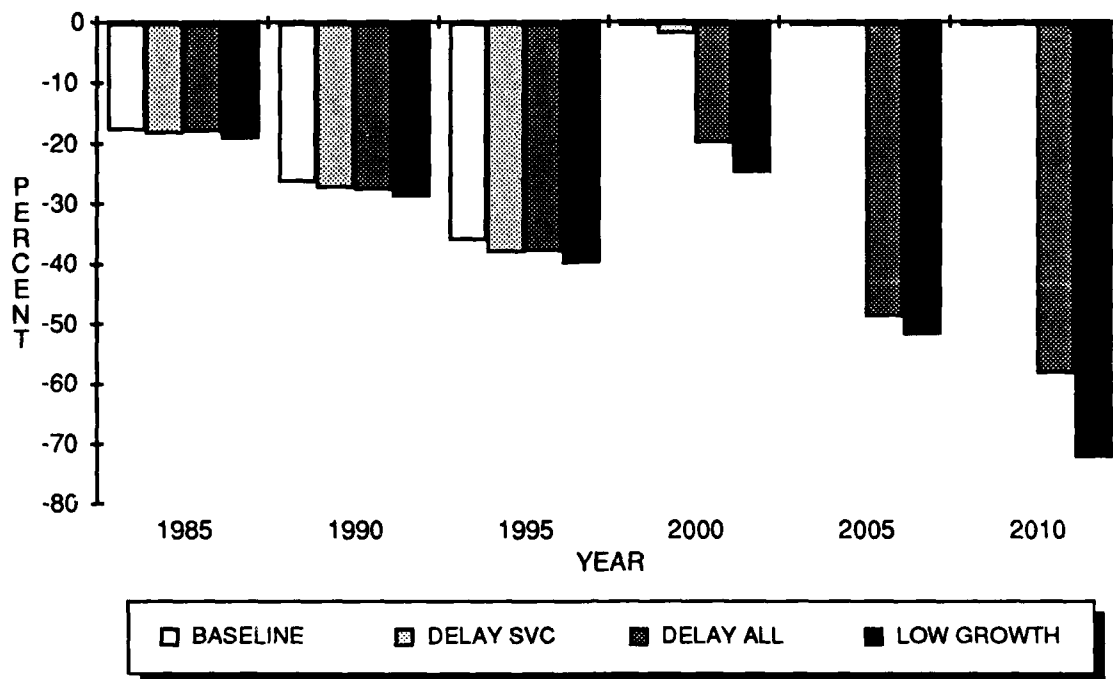


FIGURE 15b
OUTPUT LEVELS - HEAVY MACHINERY

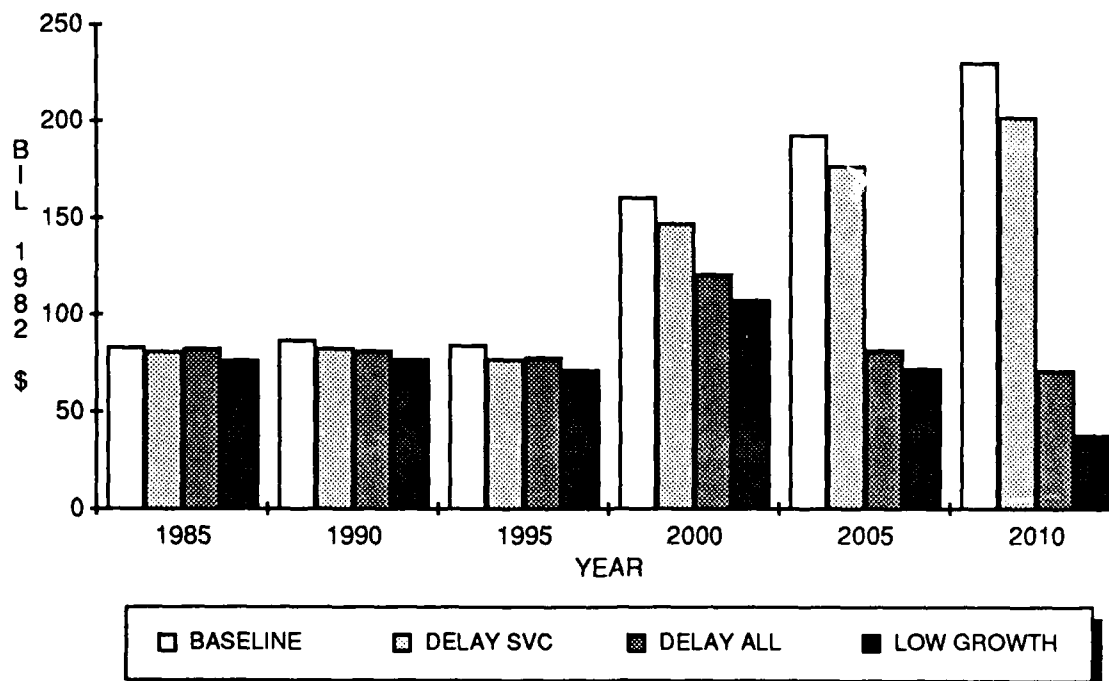


FIGURE 16a
NET EXPORT SHARES - INDUSTRIAL MACHINERY

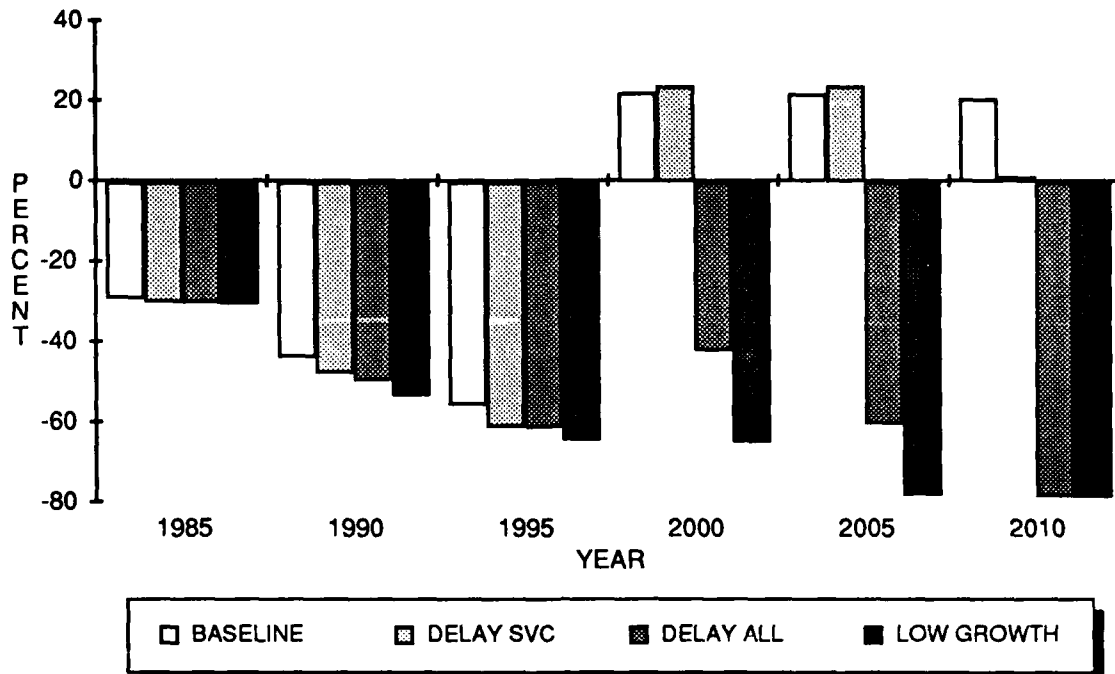


FIGURE 16b
OUTPUT LEVELS - INDUSTRIAL MACHINERY

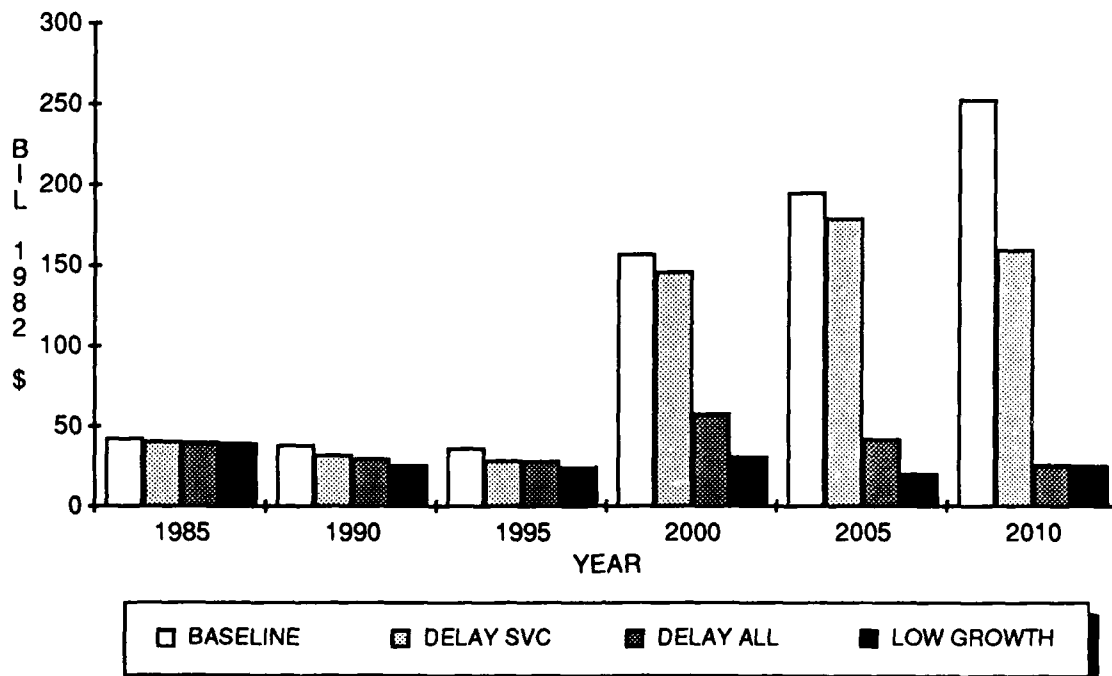


FIGURE 17a
NET EXPORT SHARES - MOTOR VEHICLES

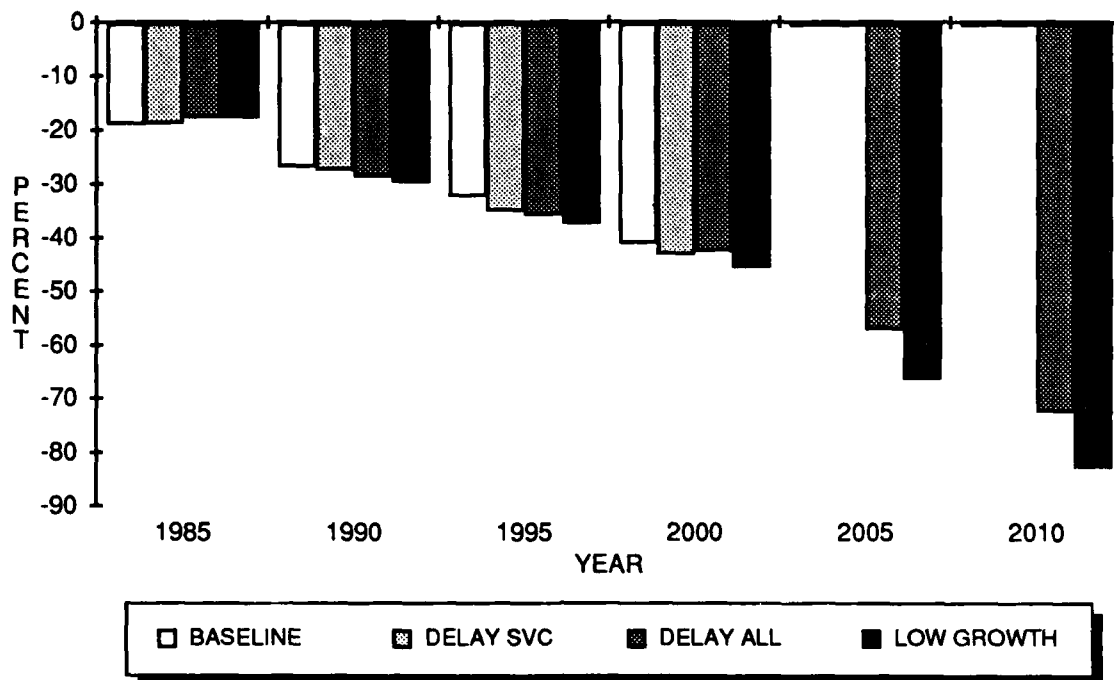


FIGURE 17b
OUTPUT LEVELS - MOTOR VEHICLES

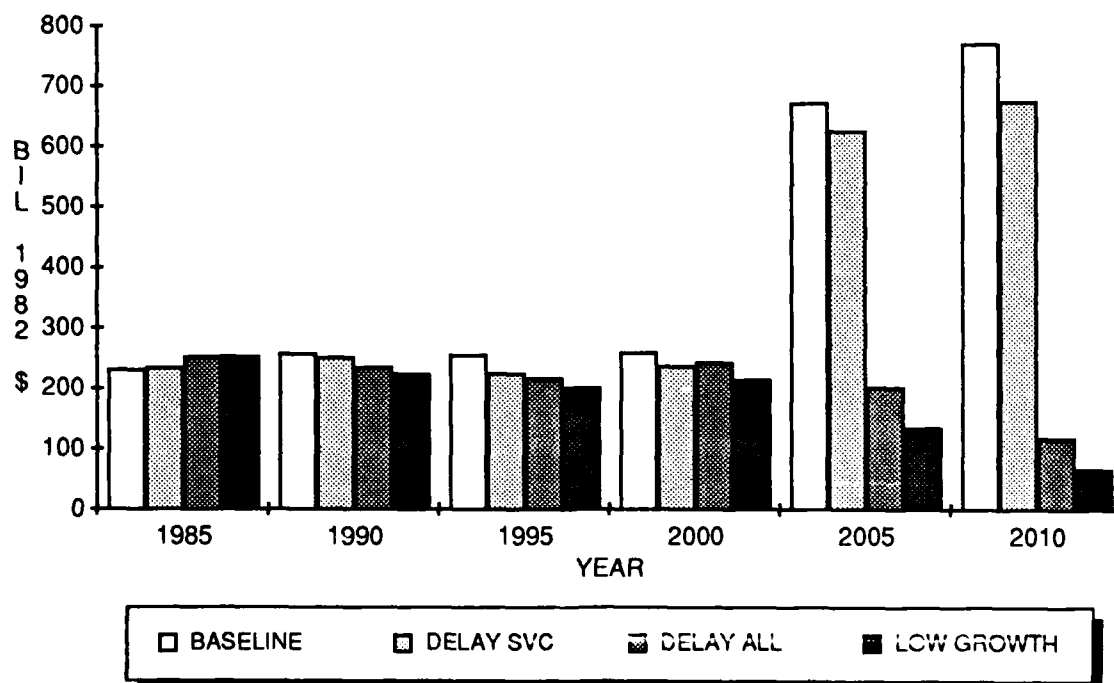


FIGURE 18
TOTAL ENERGY CONSUMPTION

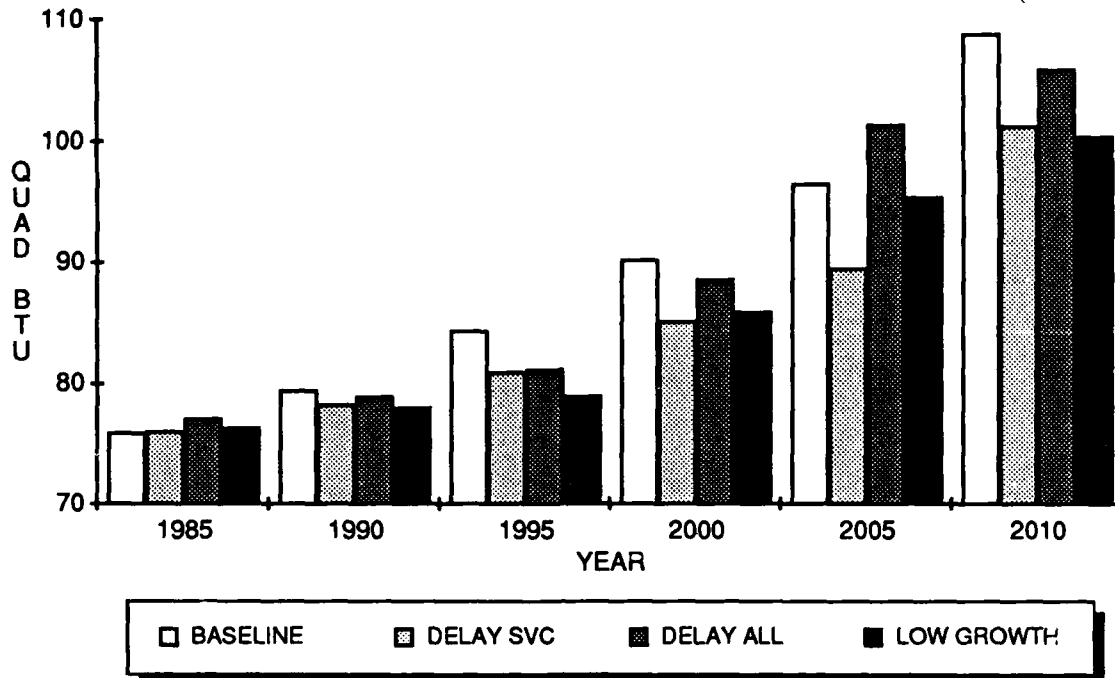


FIGURE 19
OIL PRODUCTS CONSUMPTION

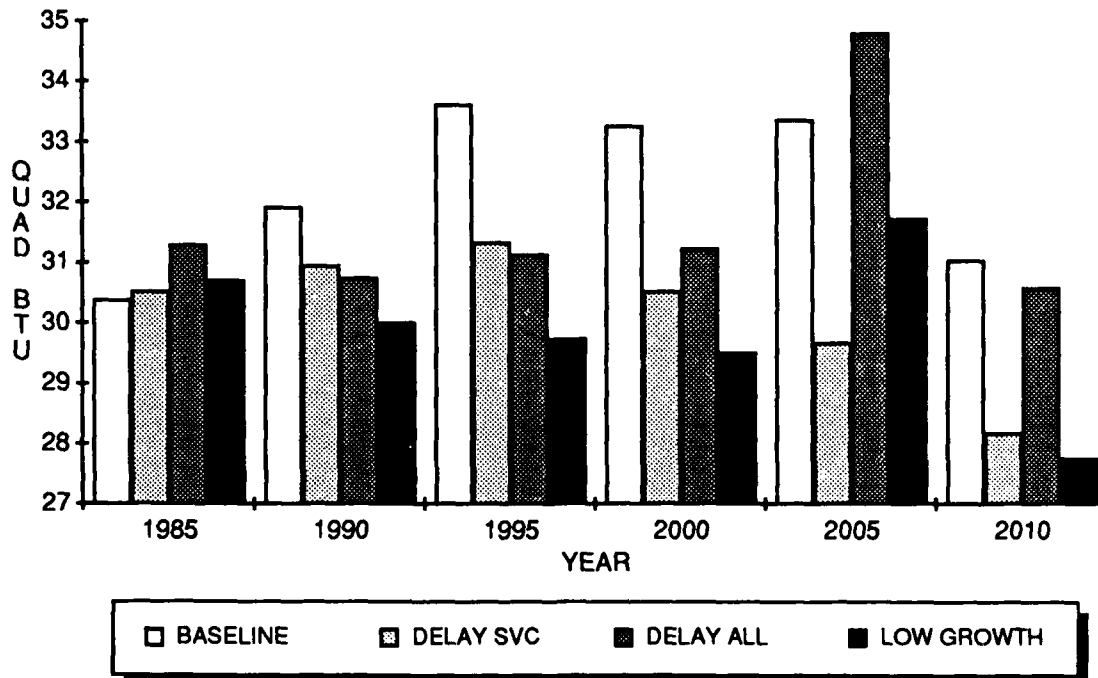


FIGURE 20
RESIDENTIAL ELECTRICITY CONSUMPTION

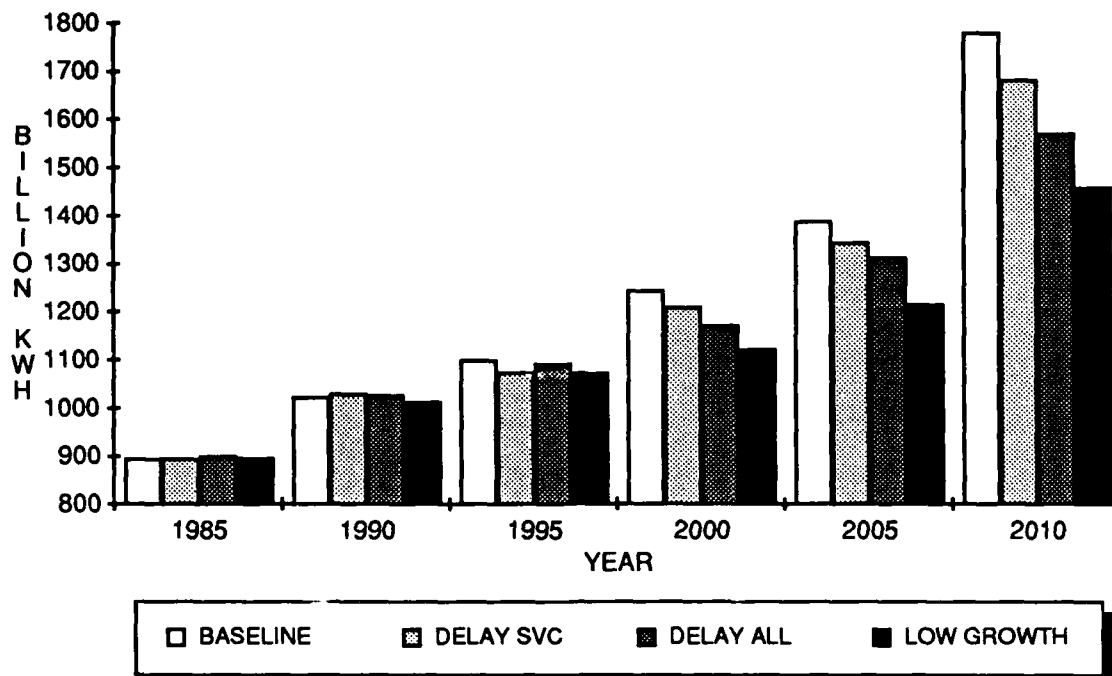


FIGURE 21
COMMERCIAL ELECTRICITY CONSUMPTION

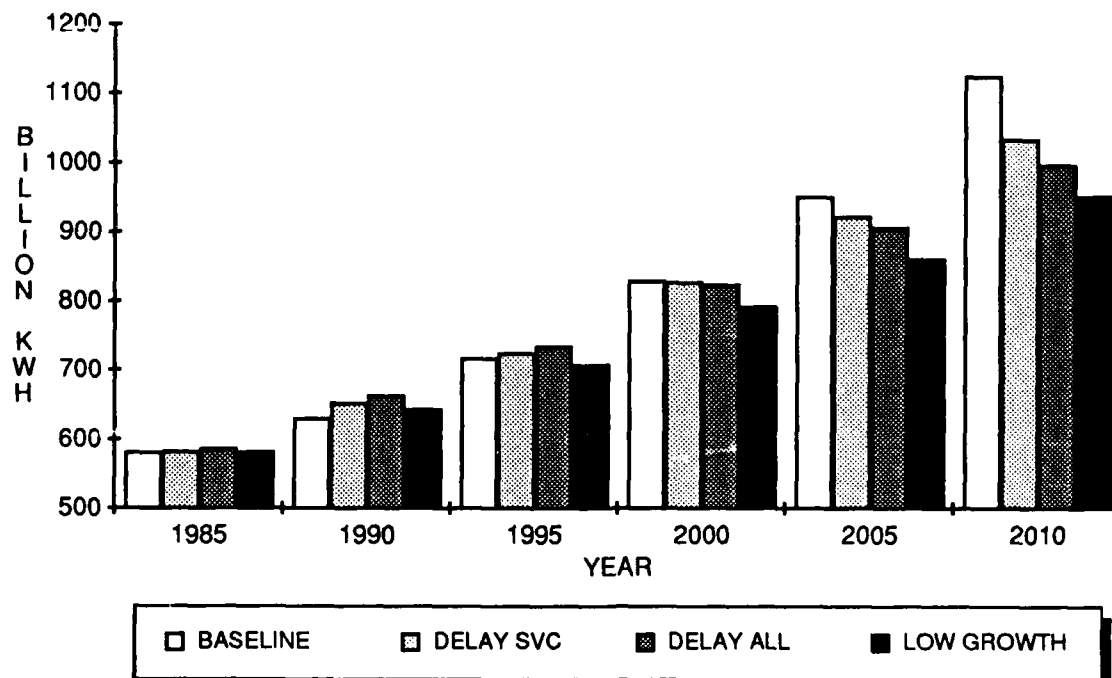


FIGURE 22
INDUSTRIAL ELECTRICITY CONSUMPTION

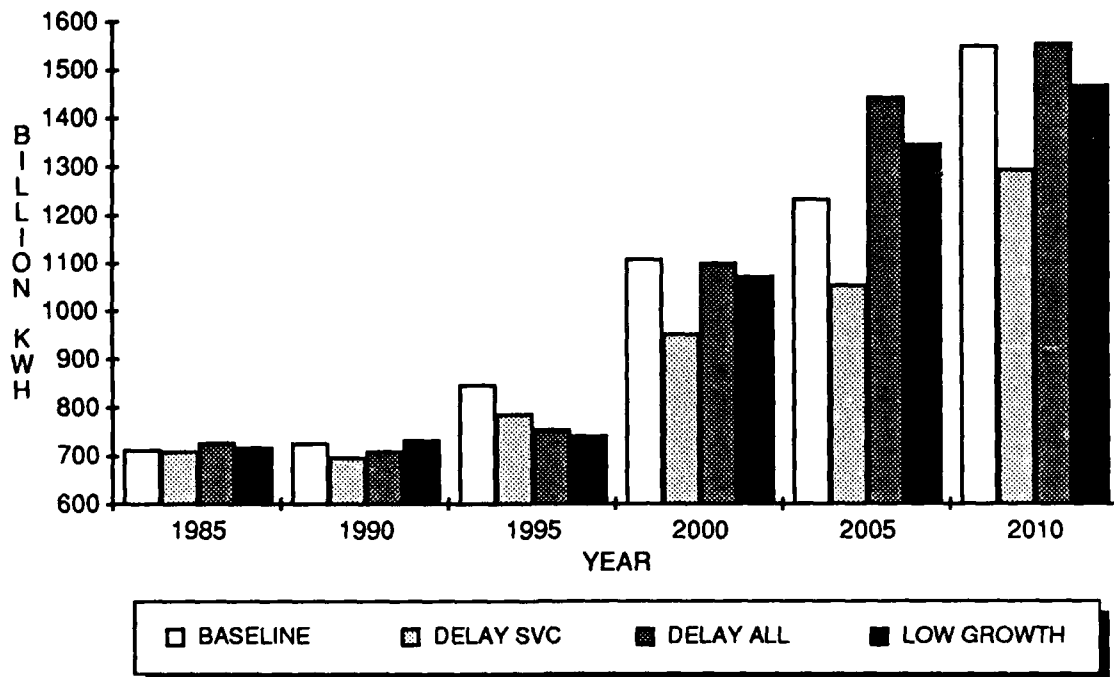


FIGURE 23
TOTAL ELECTRICITY CONSUMPTION

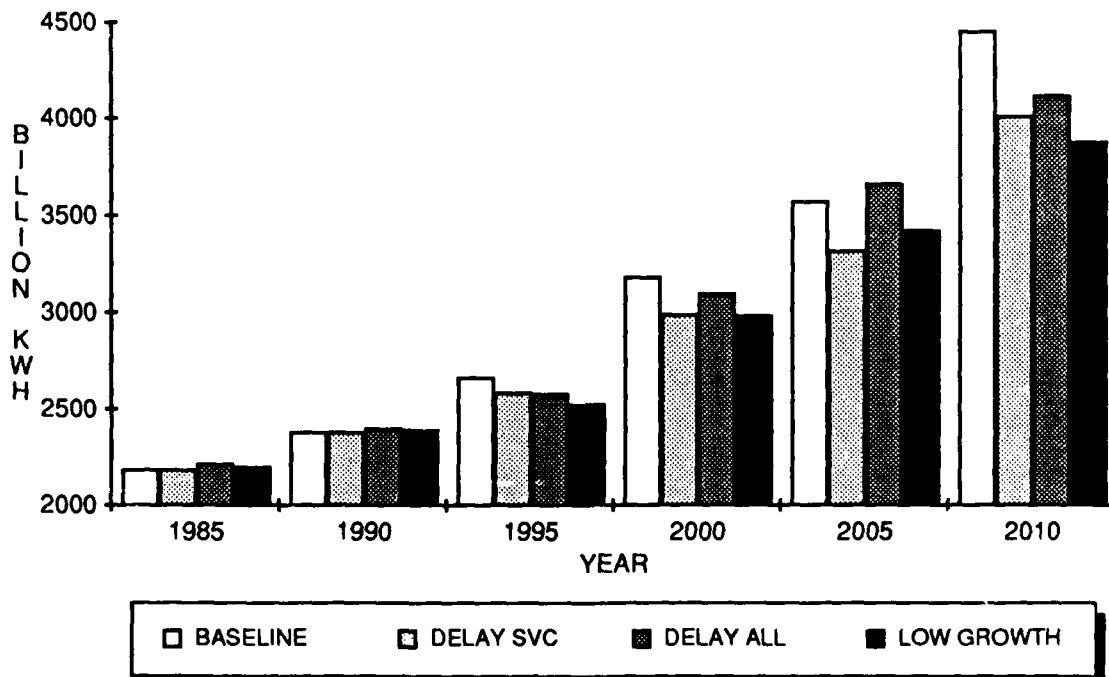


FIGURE 24a
ENERGY/GNP RATIO (1970 = 100)

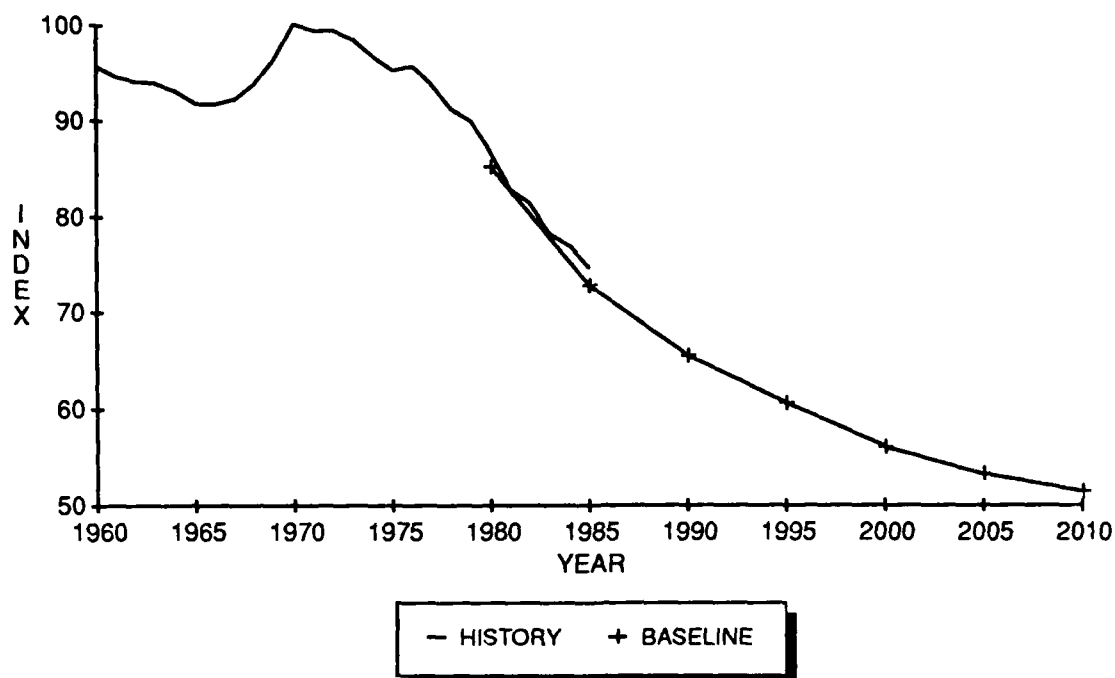


FIGURE 24b
ENERGY/GNP RATIO (1970 = 100)

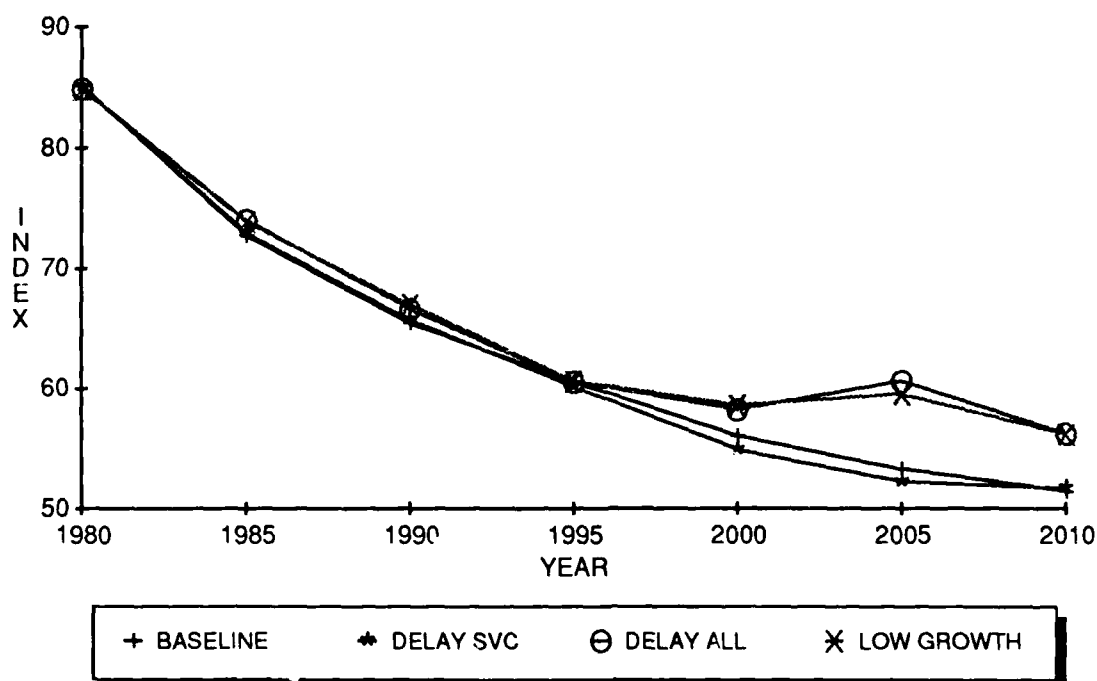


FIGURE 25a
ELECTRICITY SHARE OF TOTAL ENERGY

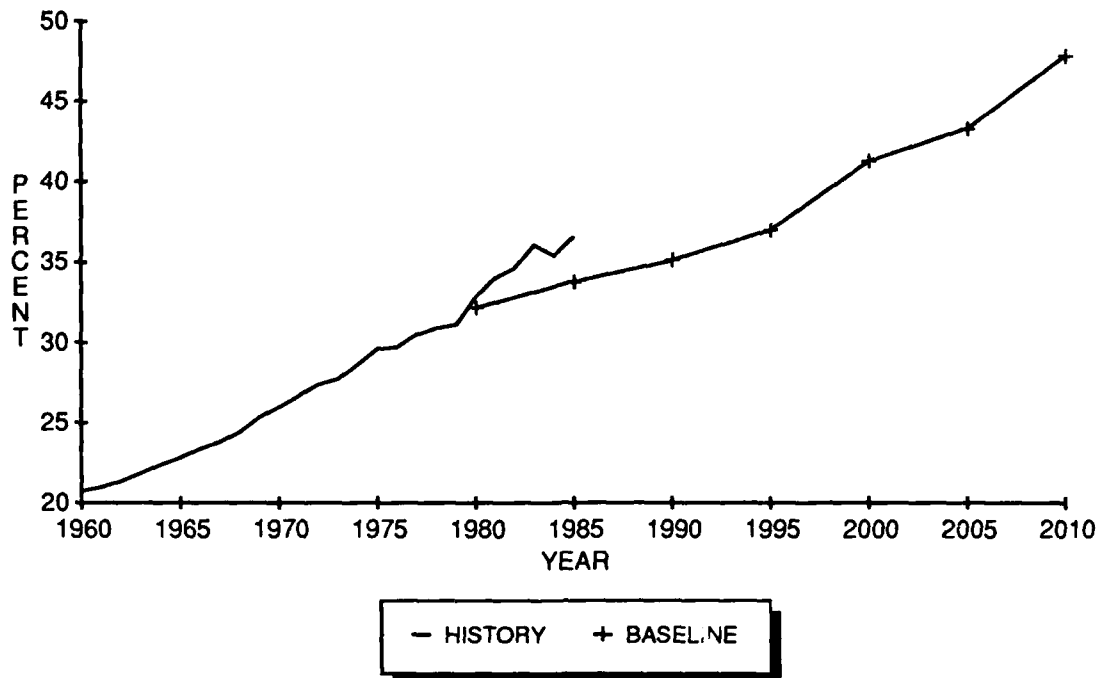
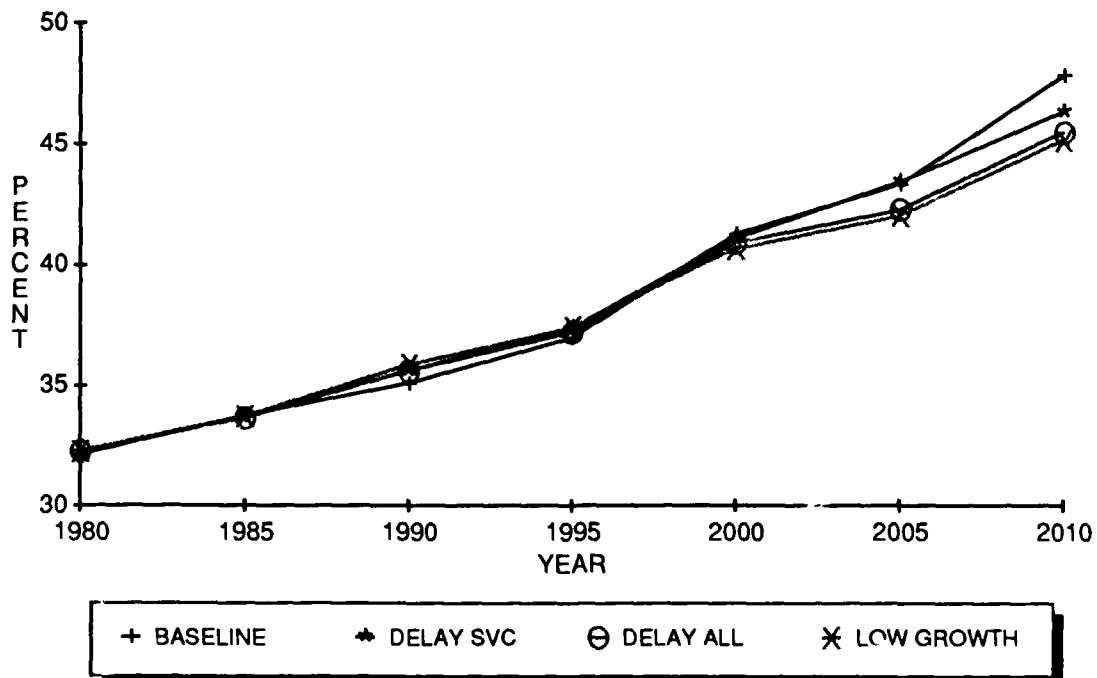


FIGURE 25b
ELECTRICITY SHARE OF TOTAL ENERGY



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ANALYZING THE EFFECTS OF TECHNOLOGICAL CHANGE:
A COMPUTABLE GENERAL EQUILIBRIUM APPROACH

SOL 88-12 Abstract

Patrick H. McAllister, John C. Stone and George B. Dantzig

Analyzing the effects of technological changes occurring simultaneously in many sectors of the economy is most meaningfully approached via mathematical models constructed in a general equilibrium framework. In order to be suited to a study of technical change, an equilibrium model should be dynamic, have a long time horizon, and allow production to be disaggregated into a large number of sectors. The size of the resulting model, however, will place it beyond the capability of existing algorithms to solve, unless some special assumptions are made. We describe a class of so-called computable general equilibrium models which have been suitably restricted in order to allow efficient computational implementation. An important example of this class is the PILOT model of the U.S. economy, which combines a process-oriented representation of production with a system of smooth consumer demand functions. Solutions of the PILOT model provide an internally consistent overall picture of the long-run consequences of technological change and of government policy and foreign market conditions in the context of technological change. We report the results of a study using PILOT to assess important differences between a "high-tech" and a "low-tech" economy, in terms of aggregate and sectoral patterns of growth, employment, and energy use over the next 25 years. The scenario analysis presented effectively illustrates the analytical advantages of the general equilibrium perspective. By far the most interesting effects of changing patterns of availability for advanced technology turn out to be *indirect* effects mediated through shifts in comparative advantage in international trade and through income effects in personal consumption. The only rigorous way to capture such effects is through the use of a general equilibrium analysis.